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Battery Life (and Death)

For product designers, an understanding of the factors affecting battery life is vitally important for managing both product performance and warranty liabilities particularly with high cost, high power batteries. Offer too low a warranty period and you won't sell any batteries/products. Overestimate the battery lifetime and you could lose a fortune.

That batteries have a finite life is due to occurrence of the unwanted chemical or physical changes to, or the loss of, the active materials of which they are made. Otherwise they would last indefinitely. These changes are usually irreversible and they affect the electrical performance of the cell.

Battery life can usually only be extended by preventing or reducing the cause of the unwanted parasitic chemical effects which occur in the cells. Some ways of improving battery life and hence reliability are considered below.

Battery cycle life is defined as the number of complete charge - discharge cycles a battery can perform before its nominal capacity falls below 80% of its initial rated capacity. Lifetimes of 500 to 1200 cycles are typical. The actual ageing process results in a gradual reduction in capacity over time. When a cell reaches its specified lifetime it does not stop working suddenly. The ageing process continues at the same rate as before so that a cell whose capacity had fallen to 80% after 1000 cycles will probably continue working to perhaps 2000 cycles when its effective capacity will have fallen to 60% of its original capacity. There is therefore no need to fear a sudden death when a cell reaches the end of its specified life. See also Performance Characteristics.

An alternative measure of cycle life is based on the internal resistance of the cell. In this case the cycle life is defined as the numer of cycles the battery can perform before its internal resistance increases to 1.3 times its initial value when new.

In both cases the cycle life depends on the depth of discharge and assumes that the battery is fully charged and discharged each cycle. If the battery is only partially discharged each cycle then the cycle life will be much greater. See Depth of Discharge below. It is therefore important that the Depth of Discharge should be stated when specifying the cycle life.

When battery systems are specified it is usual to dimension the battery in terms of its end of life capacity rather than its capacity when new.

Battery shelf life is the time an inactive battery can be stored before it becomes unusable, usually considered as having only 80% of its initial capacity as above. See also Battery Storage

Battery calendar life is the elapsed time before a battery becomes unusable whether it is in active use or inactive as above.

Chemical Changes

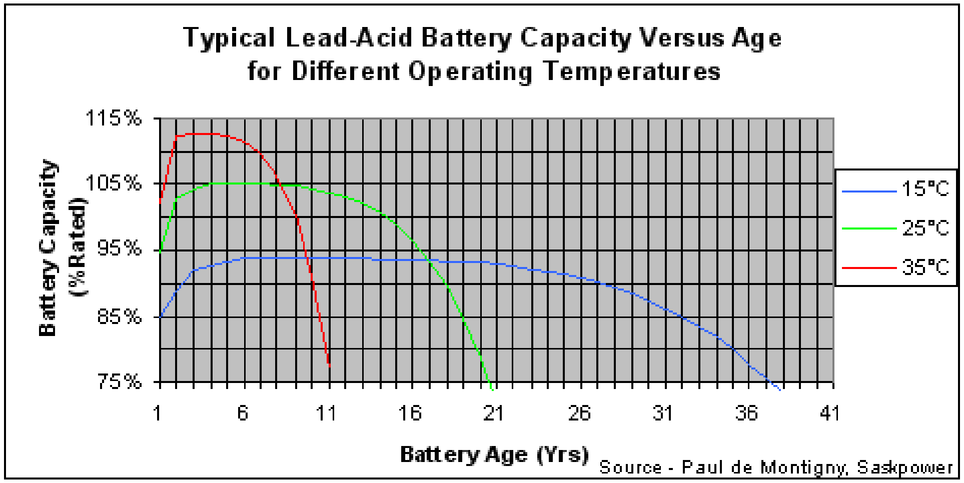
Batteries are electrochemical devices which convert chemical energy into electrical energy or vice versa by means of controlled chemical reactions between a set of active chemicals. Unfortunately the desired chemical reactions on which the battery depends are usually accompanied by unwanted chemical reactions which consume some of the active chemicals or impede their reactions. Even if the cell's active chemicals remain unaffected over time, cells can fail because unwanted chemical or physical changes to the seals keeping the electrolyte in place.

Temperature effects

Chemical reactions internal to the battery are driven either by voltage or temperature. The hotter the battery, the faster chemical reactions will occur. High temperatures can thus provide increased performance, but at the same time the rate of the unwanted chemical reactions will increase resulting in a corresponding loss of battery life. The shelf life and charge retention depend on the self discharge rate and self discharge is the result of an unwanted chemical reaction in the cell. Similarly adverse chemical reactions such as passivation of the electrodes, corrosion and gassing are common causes of reduced cycle life. Temperature therefore affects both the shelf life and the cycle life as well as charge retention since they are all due to chemical reactions. Even batteries which are specifically designed around high temperature chemical reactions, (such as Zebra batteries) are not immune to heat induced failures which are the result of parasitic reactions within the cells.

The Arrhenius equation defines the relationship between temperature and the rate at which a chemical action proceeds. It shows that the rate increases exponentially as temperature rises. As a rule of thumb, for every 10 °C increase in temperature the reaction rate doubles. Thus, an hour at 35 °C is equivalent in battery life to two hours at 25 °C. Heat is the enemy of the battery and as Arrhenius shows, even small increases in temperature will have a major influence on battery performance affecting both the desired and undesired chemical reactions.

The graph below shows how the life of high capacity tubular Ironclad Lead Acid batteries used in standby applications over may years varies with the operating temperature. Note that running at 35 °C, the batteries will deliver more than their rated capacity but their life is relatively short, whereas an extended life is possible if the batteries are maintained at 15 °C.



As an example of the importance of storage temperature conditions - Nickel-metal hydride (NiMH) chemistry in particular is very sensitive to high temperatures. Testing has shown that continuous exposure to 45°C will reduce the cycle life of a I-MH battery by 60 percent and as with all batteries, the self discharge rate doubles with each 10°C increase in temperature.

Apart from the gradual deterioration of the cell over time, under conditions of abuse, temperature effects can lead to premature failure of the cell. This can happen even under normal operating conditions if the rate of heat generated in the battery exceeds the rate of heat loss to the environment. In this situation the battery temperature will continue to rise leading to a condition known as thermal runaway which ultimately results in disastrous consequences.

The conclusion is that elevated temperatures during storage or use seriously affect the battery life.

See further information in the sections on Lithium Battery Failures and Thermal Management section.

Pressure effects

These problems relate to sealed cells only.

Increased internal pressure within a cell is usually the consequence of increased temperature. Several factors can play a part in causing the temperature and pressure rise. Excessive currents or a high ambient temperature will cause the cell temperature to rise and the resulting expansion of the active chemicals will in turn cause the internal pressure in the cell to rise. Overcharging also causes a rise in temperature, but more seriously, overcharging can also cause the release of gases resulting in an even greater build up in the internal pressure.

Unfortunately increased pressure tends to magnify the effects of high temperature by increasing the rate of the chemical actions in the cell, not just the desired Galvanic reaction but also other factors such as the self discharge rate or in extreme cases contributing to thermal runaway. Excessive pressures can also cause mechanical failures within the cells such as short circuits between parts, interruptions in the current path, distortion or swelling of the cell case or in the worst case actual rupture of the cell casing. All of these factors tend to reduce the potential battery life.

We should normally expect such problems to occur only in situations of abuse. However manufacturers have no control over how the user treats the cells once they have left the factory and for safety reasons, pressure release vents are built into the cells to provide a controlled release of pressure if there is the possibility that it could reach dangerous levels.

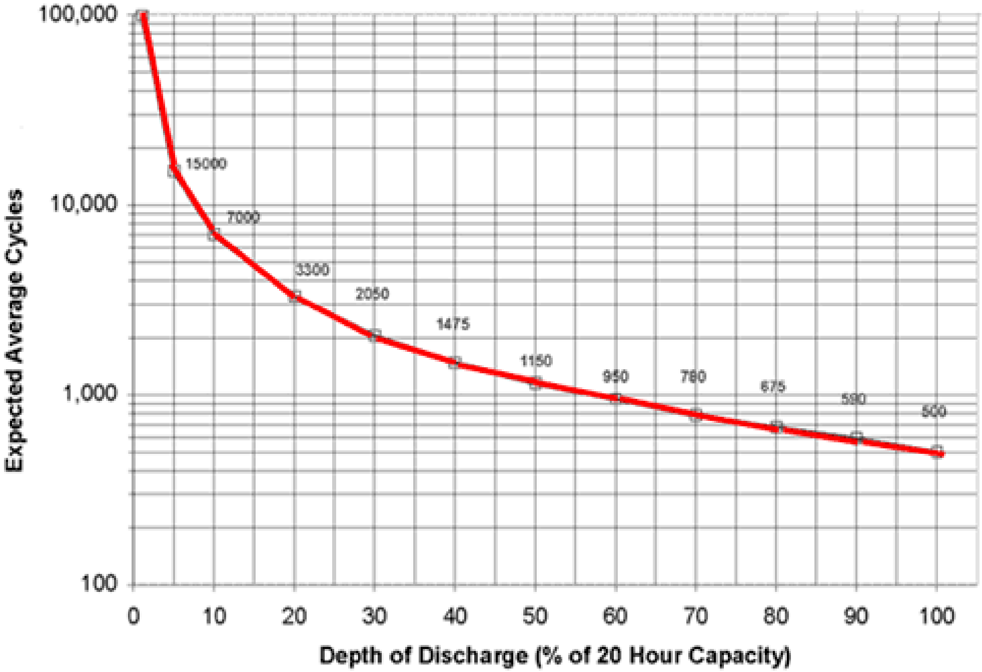
See also Protection / Venting and Loss of Electrolyte

Depth Of Discharge

The relation between the cycle life and the depth of discharge (DOD) is also logarithmic as shown in the graph below. In other words, the number of cycles yielded by a battery goes up exponentially the lower the DOD. This holds for most cell chemistries.

There are important lessons here both for designers and users. By restricting the possible DOD in the application, the designer can dramatically improve the cycle life of the product. Similarly the user can get a much longer life out of the battery by using cells with a capacity slightly more than required or by topping the battery up before it becomes completely discharged. For cells used for "microcycle" applications (small current discharge and charging pulses) a cycle life of 300,000 to 500,000 cycles is common. See also Battery Performance

Depth of Discharge vs Cycle Life



Mobile phone users typically recharge their batteries when the DOD is only about 25 to 30 percent. At this low DOD a lithium-ion battery can be expected to achieve between 5 and 6 times the specified cycle life of the battery which assumes complete discharge every cycle. Thus the cycle life improves dramatically if the DOD is reduced.

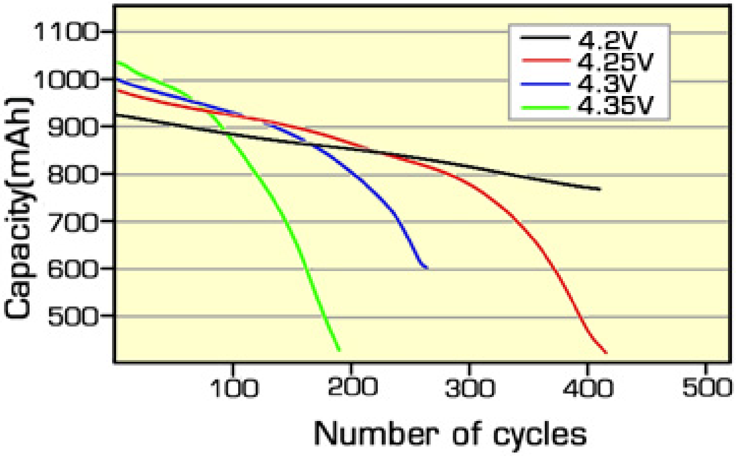
Nickel Cadmium batteries are somewhat of an exception to this. Subjecting the battery to only partial discharges gives rise to the so called memory effect (see below) which can only be reversed by deep discharging.

Some applications such as electric vehicles or marine use may require the maximum capacity to be extracted from the battery which means discharging the battery to a very high DOD. Special "deep cycle" battery constructions must be used for such applications since deep discharging may damage general purpose batteries. In particular, typical automotive SLI batteries are only designed to work down to 50% DOD, whereas traction batteries may work down to 80% to 100% DOD.

Charging Level

The cycle life of Lithium batteries can be increased by reducing the charging cut off voltage. This essentially gives the battery a partial charge instead of fully charging it, similar to working at a lower DOD as in the example above. The graph below shows the typical cycle life improvements possible.

Cycle Life and Charge Cut Off Voltage



Reducing the charging voltage cut off voltage avoids the battery reaching its maximum stress point. See also Charging Lithium Batteries and Lithium Battery Failures.

Voltage effects

Rechargeable batteries each have a characteristic working voltage range associated with the particular cell chemistry employed. The practical voltage limits are a consequence of the onset of undesirable chemical reactions which take place beyond the safe working range. Once all the active chemicals have been transformed into the composition associated with a fully charged cell, forcing more electrical energy into the cell will cause it to heat up and to initiate further unwanted reactions between the chemical components breaking them down into forms which can not be recombined. Thus attempting to charge a cell above its upper voltage limit can produce irreversible chemical reactions which can damage the cell. The increase in temperature and pressure which accompanies these events if uncontrolled could lead to rupture or explosion of the cell and the release of dangerous chemicals or fire. Similarly, discharging a cell below its recommended lower voltage limit can also result in permanent, though less dangerous, damage due to adverse chemical reactions between the active chemicals. Protection circuits are designed to keep the cell well within its recommended working range with limits set to include a safety margin. This is discussed in more detail in the section on Protection . Cycle life estimations normally assume that the cells will only be used within their specified operating limits, however this is not always the case in practice and while straying over the limits for short periods or by a minor margin will not generally cause the immediate destruction of the cell, its cycle life will most likely be affected.

For example continuously over-discharging NiMH cells by 0.2 V can result in a 40 percent loss of cycle life; and 0.3 V over-discharge of lithium-ion chemistry can result in 66 percent loss of capacity. Testing has shown that overcharging lithium cells by 0.1 V or 0.25 volts will not result in safety issues but can reduce cycle life by up to 80 percent.

Charge and discharge control are essential for preserving the life of the battery.

Cell Ageing

Charge conditioning or Formation

Cell formation is the process of transforming the active materials of a new cell into their usable form. The initial crystal structure of the electrolyte or the electrodes is determined by the manufacturing process by which these components were made and the process of coating the electrodes. This may not be the optimum structure for minimising the internal impedance of the cell and it may not give optimum contact between the electrolyte and the electrodes. The passage of current through the cell and the heating and cooling the cell is subjected to will cause small changes in the microstructure or morphology of the active chemicals.

Formation is essentially the first charge carried out at the cell manufacturer's plant under very carefully controlled conditions of current, temperature and duration to create the desired microstructure of the components and the contact between them.

With some chemical formulations it may take ten charge-discharge cycles or more before the battery is able to deliver its full power or capacity.

Growing old

Once in use however the usage profile of the cell is determined by the user. During the lifetime of the cell, even if there is no undesirable change in the chemical composition of the materials, the morphology of the active components will continue to change, usually for the worse. The result is that the performance of the cell gradually deteriorates until eventually the cell becomes unserviceable.

As the cell ages, both the chemical composition and the crystalline structure of the materials changes, larger crystals tend to form and metallic dendrites may be formed on the electrodes.

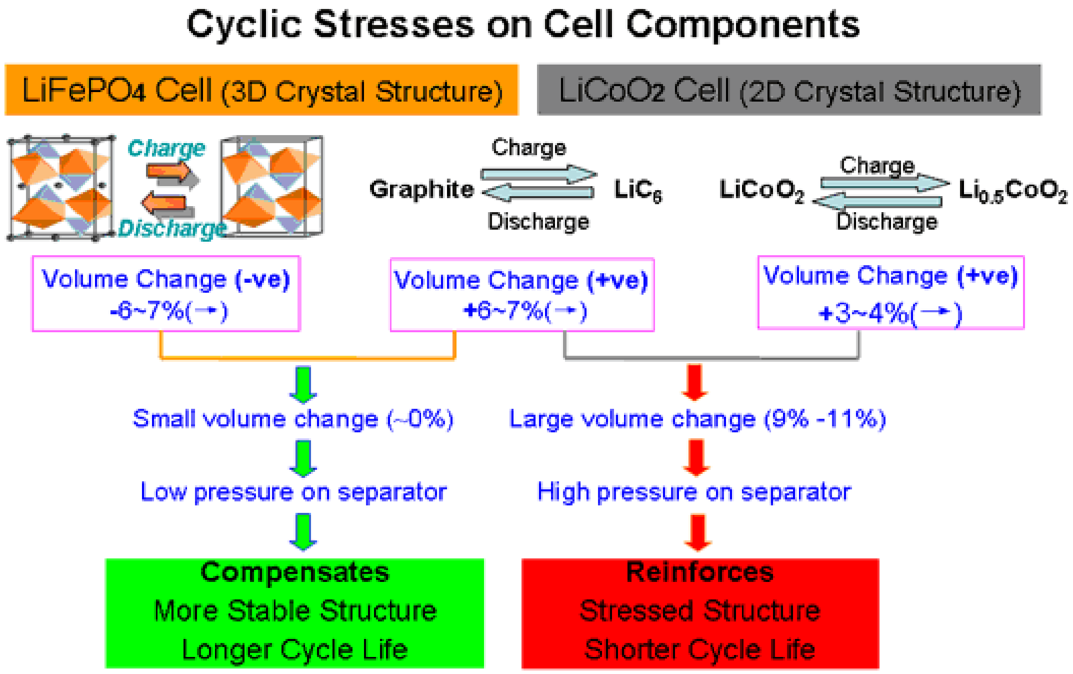
There are several consequences of these changes:-

- As the smaller crystals created during formation of the cell grow to a larger size the internal impedance of the cell increases and the cell capacity is reduced.
- The crystal and dendritic growth cause a swelling of the electrodes which in turn exerts pressure on the electrolyte and the separator. As the electrodes press closer to each other the self discharge of the cell tends to increase.
- In extreme cases, the separator may be penetrated by dendritic or crystal growth resulting in even higher self discharge or a short circuit.

Once a battery exhibits high self discharge, no remedy is available to reverse its effect.

Cyclic Stresses

In Lithium ion cells the insertion or ejection of the Lithium ions into and out of the intercalation spaces during charging and discharging causes the electrode materials to swell or contract. Repetitive cycling can weaken the electrode structure reducing its adhesion to the current collector causing the cell to swell. This can lead to reduction in charge capacity and ultimately failure of the cell.



The degree of expansion or contraction of the electrode structure depends on the materials used. The volume change in of each of the electrodes in Lithium Cobalt cells tends to reinforce each other causing the cell to swell whereas volume changes of the electrodes in Lithium Phosphate cells tends to compensate for eachother keepng swelling to a minimum.

Using Silicon as the anode material instead of Carbon offers the possiblity of very high charge capacities ten times better than Carbon. Unfortunately Silicon anodes are subject to a 400% volume change during charging which leads to physical breakdown of anode coating. This is still an unsolved problem and various possible solutions are currently being investigated.

Memory Effect

The so called "Memory Effect" is another manifestation of the changing morphology of the cell components with age. It appears that Nicad cells could "remember" how much discharge was required on previous discharges and would only accept that amount of charge in subsequent charges. Nickel metal hydride cells suffer from the same problem but to a lesser extent. What happens in fact is that repeated shallow charges cause the crystalline structure of the electrodes to change as noted above and this causes the internal impedance of the cell to increase and its capacity to be reduced. Long slow charges such as trickle charging tend to promote this undesirable crystal growth, as does high temperatures and so should be avoided.

Reconditioning or Restoration

It is often possible to restore a cell to, or near to, its full capacity essentially by repeating the formation process to break down the larger crystals into their previous smaller size. One or more deep discharges below 1.0 V/cell with a very low controlled current is enough to cause a change to the molecular structure of the cell to rebuild of its original chemical composition. Thus giving the cell electric shock treatment can make it lose its memory. This cure doesn't necessarily work with older cells, set in their ways, whose crystal structure has become ingrained and could actually make them worse by increasing the self discharge rate. These older cells nearing the end of their useful life should be retired.

Passivation

Passivation is another secondary chemical action which may occur in a battery. A resistive layer forms on the electrodes in some cells due to cycling, or after prolonged storage. This may be in the form of a chemical deposit or simply a change in the crystalline structure of the electrode surface. This layer impedes the chemical reactions of the cell and its ability to deliver current as well as increasing the cell's internal resistance. This barrier must normally be removed to enable proper operation of the cell, however in some cases passivation can bring a benefit by reducing the cell's self discharge. As with reconditioning above, applying controlled charge/discharge cycles often helps in recovering the battery for use.

Loss of Electrolyte

Any reduction in the volume of the cell's active chemicals will of course directly reduce the cell's electrical capacity. At the same time the cell's potential cycle life will automatically be reduced since the cell's useful life is defined to be over when its capacity is reduced by 20%.

Electrolyte may be lost from leakage due to the deterioration over time of the seals closing the cells. Even with good seals the solvents in the electrolyte may eventually permeate through the seal over a prolonged period causing the electrolyte to dry out particularly if the cells are stored in a dry atmosphere or if the cell contents are under pressure due to high temperatures.

However the loss of electrolyte is not just due to the physical leakage of the electrolyte from the cell, the electrolyte may be effectively lost to the electrochemical system because it has been transformed or decomposed into another inactive compound which may or may not remain inside the cell casing. Corrosion is an example of this as are other compounds which may have been caused by overheating or abuse. Gassing and evaporation are two other mechanisms by which electrolyte may be lost thus causing an irreversible loss in the capacity of the cell.

Recombinant Systems

In order to prevent the loss of electrolyte from secondary cells in which the electrochemical charging cycle produces gaseous products the cells must be sealed. Closed cycle systems in which the gases are made to recombine to recover the active chemicals are called recombinant systems. Nicads and SLA batteries use recombinant designs.

Venting

Although most modern cells have a sealed construction to prevent loss of electrolyte, they usually have a vent to relieve pressure if there is a danger of the cell rupturing due to excessive pressure. Whenever a vent operates, it releases or expels some of the active chemicals to the atmosphere and hence reduces the cell's capacity.

To determine whether electrolyte loss through venting has occurred, the suspect cell can be weighed and its weight compared with the weight of a known good cell of the same make and capacity.

Leakage

Leakage used to be a major problem with Zinc Carbon cells. This was because the zinc casing took part in the electrochemical discharge reaction. During the lifetime of the cell, the cell walls become progressively thinner as the zinc is consumed until they become perforated allowing the electrolyte to escape. The escaping chemicals also create corrosion on the battery terminals compounding the problem. New cell constructions and modern materials have significantly diminished this problem. Nevertheless some cells may still leak due to poor sealing or corrosion problems.

Manufacturing Tolerances

Battery life is also affected by variations in the materials and components used in manufacturing the cells and although manufacturers try to keep these variations to a minimum there will always be a spread in the properties of the materials used within the tolerances allowed. Ultimately the consequences of these tolerance spreads will be reflected in the lifetime of the cells. These factors also explain the wide disparity in performance of similar cells from different manufacturers.

Chemical Composition

The quality of the active chemicals may vary, particularly if more than one source of supply is used. This may affect the concentration of the chemicals or the level of impurities present and these factors in turn affect the cell voltage, the internal impedance and the self discharge rates.

Dimensional Accuracy

Variations in the dimensions of the components or in the placement of the parts making up the cell can also affect the cell performance and life expectancy. Burrs and slight misalignments can cause short circuits, maybe not immediately, but after repeated temperature cycling. The filling of the electrolyte may be incomplete resulting in a corresponding reduction in cell capacity. The granularity of the chemicals and the surface finish on the electrodes both affect the current carrying capacity of the cells.

Interactions Between Cells

This can occur in multi-cell batteries and is a consequence of the spread of operating characteristics of the individual cells in the pack. This may be due to manufacturing tolerances as noted above or uneven temperature conditions across the pack or non uniform ageing patterns which cause some cells to accept less charge than others. The result is that in a series chain, a weak cell with reduced capacity will reach its full charge before the rest of the cells in the chain and become overcharged as the charger attempts to charge the overall cell chain to its nominal voltage. As already noted, overcharging causes the cell to overheat resulting in expansion of the active chemicals as well as the possible gassing of the electrolyte. These factors in turn cause the internal pressure to rise, resulting in overstress and possible damage to the cell. This will be repeated with every charge-discharge cycle causing the cell to become more stressed and hence even weaker until it eventually fails. On the other hand, if for some reason the weak cell can not reach full charge, perhaps due to a very high self discharge, or in an extreme case, a short circuited cell, then the good cells, rather than the weaker cell, could possibly become overcharged.

Damage to weaker cells can also continue during the discharge cycle. When discharged in a series configuration the capacity of the weakest cell in the chain will be depleted before the others. If the discharge is continued (to discharge the remaining good cells), the voltage on the low capacity cell will reach zero then reverse due to the IR voltage drop across the cell. Subsequent heat and pressure build up within the cell due to "cell reversal" can then cause catastrophic failure.

The initial tolerance spread which caused these interactions may be very low but it can build up over time as the damage increases with every charge-discharge cycle until the weak cells eventually fail.

Improving Battery Life

The simplest and most obvious way of getting the maximum life out of a battery is to ensure that it always works well within its designed operating limits. There are however some further actions which can be taken to increase the battery life. These are summarised below and in depth explanations and examples are available by following the links.

Charging

As noted in the section on Charging most battery failures are due to inappropriate charging. The use of intelligent chargers and safety systems which prevent the connection of unapproved chargers to the battery may not extend battery life but at least they can prevent it from being cut short.

Battery Management

Battery management is essentially the method of keeping the cells within their desired operating limits during both charging and discharging either by controlling the load on the battery or by isolating the battery from the load if the load can not be controlled. See Battery Management

Cell Balancing

As noted above, in multi-cell batteries problems could arise from interactions between the cells caused by small differences in the characteristics of the individual cells making up the battery. Cell balancing is designed to equalise the charge on every cell in the pack and prevent individual cells from becoming over stressed thus prolonging the life of the battery. See Cell Balancing

Load Sharing

For pulsed applications the peak load on the battery can be reduced by placing a large value capacitor in parallel with the battery. Energy for large instantaneous loads is supplied by the capacitor effectively reducing the duty cycle and stress on the battery. The capacitor recharges during the quiescent periods. Claims of a sixty percent increase in cycle life are made for this technique.

Another benefit of this arrangement is that since the battery supplies less of the instantaneous peak load current, the voltage drop across the battery will be lower. For high power pulses this voltage drop can be very significant.

See Capacitors and Supercapacitors.

Reformation/Reconditioning

As noted above some cells suffering capacity loss can be restored by repeating the formation process thus extending their life. See Reformation/ Reconditioning

Demand Management

The "effective" life of a battery in a particular application can also be extended by controlling the load which the application places on the battery. This does not actually improve the battery performance, instead it reduces the load that the battery has to supply. See Demand Management

Premature Death (Murder)

The most likely cause of premature failure of a battery is abuse, subjecting a battery to conditions for which it was never designed.

Apart from obvious physical abuse, the following examples should also be considered abuse, whether deliberate, inadvertent or through poor maintenance disciplines.

- Drawing more current than the battery was designed for or short circuiting the battery.
- Using undersized batteries for the application.
- Circuit or system designs which subject the battery to repeated "coup de fouet" (whiplash) effects. This effect is a temporary, severe voltage drop which occurs when a heavy load is suddenly placed on the battery and is caused by the inability of the rate of the chemical action in the battery to accommodate the instantaneous demand for current.
- Operating or storing the battery in too high or too low ambient temperatures.
- Using chargers designed for charging batteries with a different cell chemistry.
- Overcharging - either to too high a voltage or for too long a period.
- Over-discharging - allowing the battery to become completely discharged.
- In aqueous batteries - allowing electrolyte level to fall below the recommended minimum.
- In aqueous batteries - topping up with tap water instead of distilled water (or inappropriate electrolyte).
- Subjecting the battery to excessive vibration or shock.

Battery designers try to design out the possibility of abuse wherever possible but ultimately the life of the battery is in the user's hands.

See also Why Batteries Fail, Lithium Battery Failures, Battery Safety and Battery Protection Methods

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Performance Characteristics

This section describes the main parameters which are used to characterise cell performance. An appreciation of these characteristics is essential for choosing the optimum battery for an application.

Discharge Curves

Energy cells have been developed for a wide range of applications using a variety of different technologies, resulting in a wide range of available performance characteristics. The graphs below show some of the main factors an applications engineer should take into account when specifying a battery to match the performance requirements of the end product.

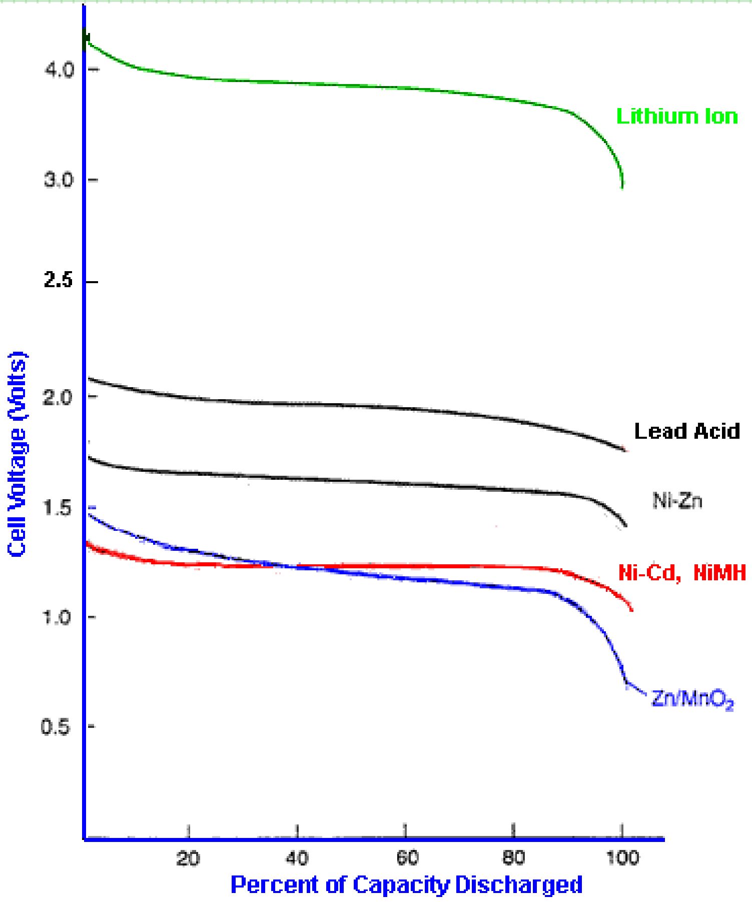
Cell Chemistry

The nominal voltage of a galvanic cell is fixed by the electrochemical characteristics of the active chemicals used in the cell, the so called cell chemistry. The actual voltage appearing at the terminals at any particular time, as with any cell, depends on the load current and the internal impedance of the cell and this varies with, temperature, the state of charge and with the age of the cell.

The graph below shows typical discharge discharge curves for cells using a range of cell chemistries when discharged at 0.2C rate. Note that each cell chemistry has its own characteristic nominal voltage and discharge curve. Some chemistries such as Lithium Ion have a fairly flat discharge curve while others such as Lead acid have a pronounced slope.

The power delivered by cells with a sloping discharge curve falls progressively throughout the discharge cycle. This could give rise to problems for high power applications towards the end of the cycle. For low power applications which need a stable supply voltage, it may be necessary to incorporate a voltage regulator if the slope is too steep. This is not usually an option for high power applications since the losses in the regulator would rob even more power from the battery.

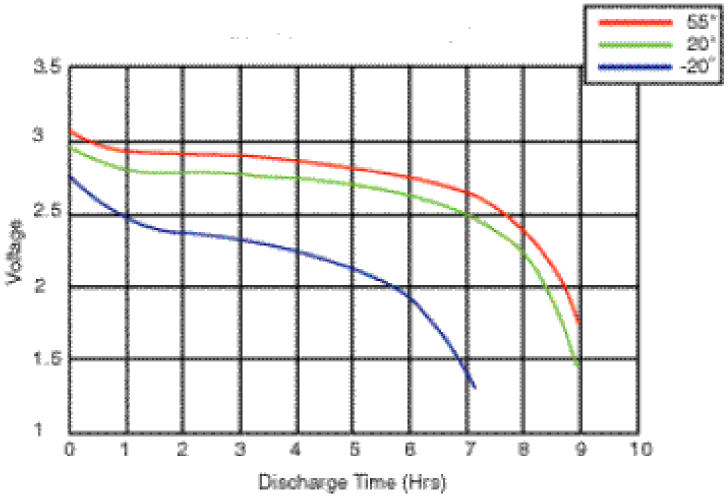
A flat discharge curve simplifies the design of the application in which the battery is used since the supply voltage stays reasonably constant throughout the discharge cycle. A sloping curve facilitates the estimation of the State of Charge of the battery since the cell voltage can be used as a measure of the remaining charge in the cell. Modern Lithium Ion cells have a very flat discharge curve and other methods must be used to determine the State of Charge



The X axis shows the cell characteristics normalised as a percentage of cell capacity so that the shape of the graph can be shown independent of the actual cell capacity. If the X axis was based on discharge time, the length of each discharge curve would be proportional to the nominal capacity of the cell.

Temperature Characteristics

Cell performance can change dramatically with temperature. At the lower extreme the electrolyte may freeze setting a lower limit on the operating temperature, while at the upper extreme the active chemicals may break down destroying the battery. In between these limits the cell performance generally improves with temperature. See also Thermal Management and Battery Life for more details.



The above graph shows how the performance of Lithium Ion batteries deteriorates as the operating temperature decreases.

Self Discharge Characteristics

The self discharge rate is a measure of how quickly a cell will lose its energy while sitting on the shelf due to unwanted chemical actions within the cell. The rate depends on the cell chemistry and the temperature.

Cell Chemistry

The following shows the typical shelf life for some primary cells:

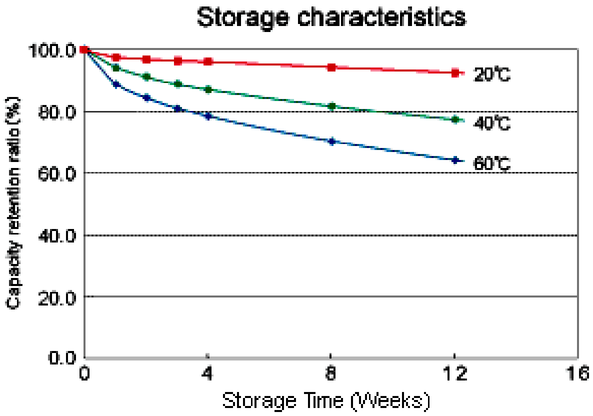
- Zinc Carbon (Leclanché) 2 to 3 years
- Alkaline 5 years
- Lithium 10 years or more

Typical self discharge rates for common rechargeable cells are as follows:

- Lead Acid 4% to 6% per month
- Nickel Cadmium 15% to 20% per month
- Nickel Metal Hydride 30% per month
- Lithium 2% to 3% per month

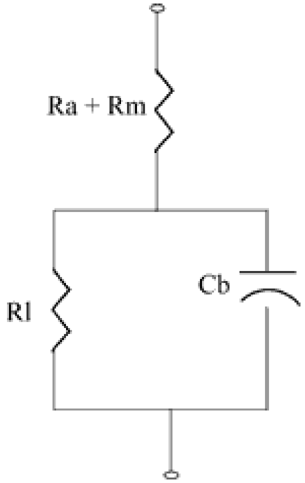
Temperature Effects

The rate of unwanted chemical reactions which cause internal current leakage between the positive and negative electrodes of the cell, like all chemical reactions, increases with temperature thus increasing the battery self discharge rate. See also Battery Life . The graph below shows typical self discharge rates for a Lithium Ion battery.



Internal Impedance

The internal impedance of a cell determines its current carrying capability. A low internal resistance allows high currents.



Battery Equivalent Circuit

The diagram on the right shows the equivalent circuit for an energy cell.

- **Rm** is the resistance of the metallic path through the cell including the terminals, electrodes and inter-connections.
- **Ra** is the resistance of the electrochemical path including the electrolyte and the separator.
- **Cb** is the capacitance of the parallel plates which form the electrodes of the cell.
- **Ri** is the non-linear contact resistance between the plate or electrode and the electrolyte.

Typical internal resistance is in the order of milliohms.

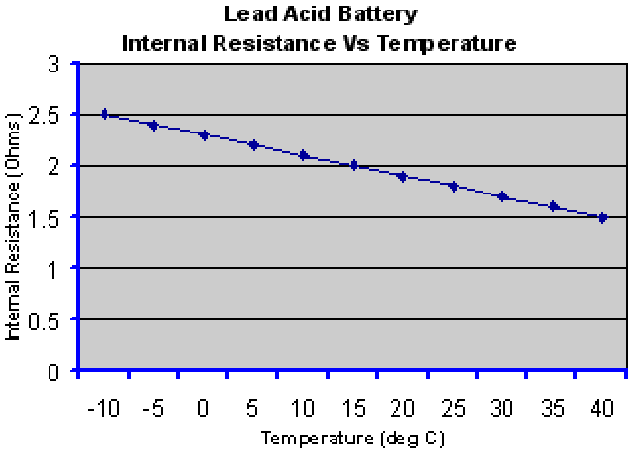
Effects of Internal Impedance

When current flows through the cell there is an IR voltage drop across the internal resistance of the cell which decreases the terminal voltage of the cell during discharge and increases the voltage needed to charge the cell thus reducing its effective capacity as well as decreasing its charge/ discharge efficiency. Higher discharge rates give rise to higher internal voltage drops which explains the lower voltage discharge curves at high C rates. See "Discharge Rates" below.

The internal impedance is affected by the physical characteristics of the electrolyte, the smaller the granular size of the electrolyte material the lower the impedance. The grain size is controlled by the cell manufacturer in a milling process.

Spiral construction of the electrodes is often used to maximise the surface area and thus reduce internal impedance. This reduces heat generation and permits faster charge and discharge rates.

The internal resistance of a galvanic cell is temperature dependent, decreasing as the temperature rises due to the increase in electron mobility. The graph below is a typical example.



Thus the cell may be very inefficient at low temperatures but the efficiency improves at higher temperatures due to the lower internal impedance, but also to the increased rate of the chemical reactions. However the lower internal resistance unfortunately also causes the self discharge rate to increase. Furthermore, cycle life deteriorates at high temperatures. Some form of heating and cooling may be required to maintain the cell within a restricted temperature range to achieve the optimum performance in high power applications.

The internal resistance of most cell chemistries also tends to increase significantly towards the end of the discharge cycle as the active chemicals are converted to their discharged state and hence are effectively used up. This is principally responsible for the rapid drop off in cell voltage at the end of the discharge cycle.

In addition the Joule heating effect of the I^2R losses in the internal resistance of the cell will cause the temperature of the cell to rise.

The voltage drop and the I^2R losses may not be significant for a 1000 mAh cell powering a mobile phone but for a 100 cell 200 Ah automotive battery they can be substantial. Typical internal resistance for a 1000mA Lithium mobile phone battery is around 100 to 200mOhm and around 1mOhm for a 200Ah Lithium cell used in an automotive battery.

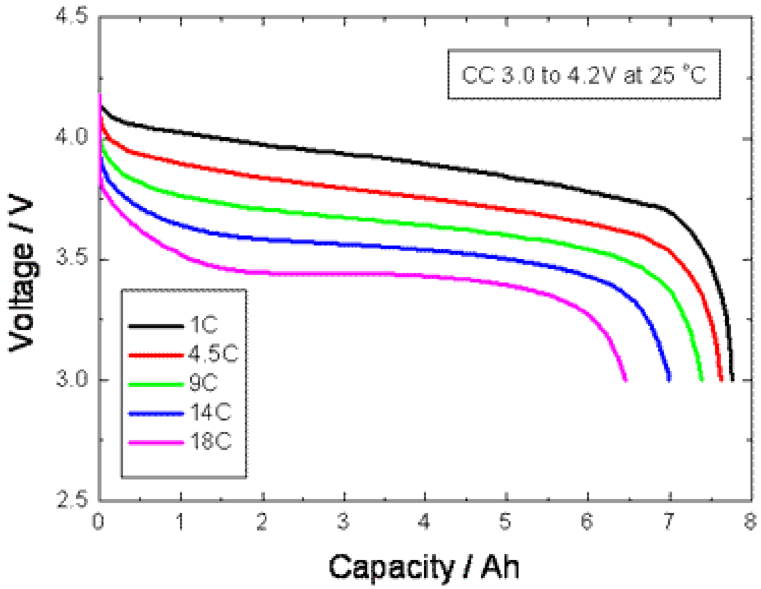
Operating at the C rate the voltage drop per cell will be about 0.2 volts in both cases, (slightly less for the mobile phone). The I^2R loss in the mobile phone will be between 0.1 and 0.2 Watts. In the automotive battery however the voltage drop across the whole battery will be 20 Volts and I^2R power loss dissipated as heat within the battery will be 40 Watts per cell or 4KW for the whole battery. This is in addition to the heat generated by the electrochemical reactions in the cells.

As a cell ages, the resistance of the electrolyte tends to increase. Aging also causes the surface of the electrodes to deteriorate and the contact resistance builds up and at the same the effective area of the plates decreases reducing its capacitance. All of these effects increase the internal impedance of the cell adversely affecting its ability to perform. Comparing the actual impedance of a cell with its impedance when it was new can be used to give a measure or representation of the age of a cell or its effective capacity. Such measurements are much more convenient than actually discharging the cell and can be taken without destroying the cell under test. See "Impedance and Conductance Testing"

The internal resistance also influences the effective capacity of a cell. The higher the internal resistance, the higher the losses while charging and discharging, especially at higher currents. This means that for high discharge rates the lower the available capacity of the cell. Conversely, if it is discharged over a prolonged period, the AmpHour capacity is higher. This is important because some manufacturers specify the capacity of their batteries at very low discharge rates which makes them look a lot better than they really are.

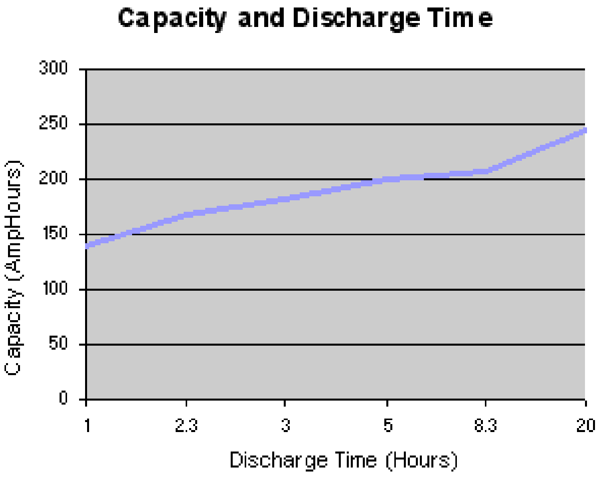
Discharge Rates

The discharge curves for a Lithium Ion cell below show that the effective capacity of the cell is reduced if the cell is discharged at very high rates (or conversely increased with low discharge rates). This is called the capacity offset and the effect is common to most cell chemistries.



If the discharge takes place over a long period of several hours as with some high rate applications such as electric vehicles, the effective capacity of the battery can be as much as double the specified capacity at the C rate. This can be most important when dimensioning an expensive battery for high power use. The capacity of low power, consumer electronics batteries is normally specified for discharge at the C rate whereas the SAE uses the discharge over a period of 20 hours (0.05C) as the standard condition for measuring the Amphour capacity of automotive batteries. The graph below shows that the effective capacity of a deep discharge lead acid battery is almost doubled as the discharge rate is reduced from 1.0C to 0.05C. For discharge times less than one hour (High C rates) the effective capacity falls off dramatically.

The effectiveness of charging is similarly influenced by the rate of charge. An explanation of the reasons for this is given in the section on Charging Times .



There are two conclusions to be drawn from this graph:

- Care should be exercised when comparing battery capacity specifications to ensure that comparable discharge rates are used.
- In an automotive application, if high current rates are used regularly for hard acceleration or for hill climbing, the range of the vehicle will be reduced.

Notes: For information

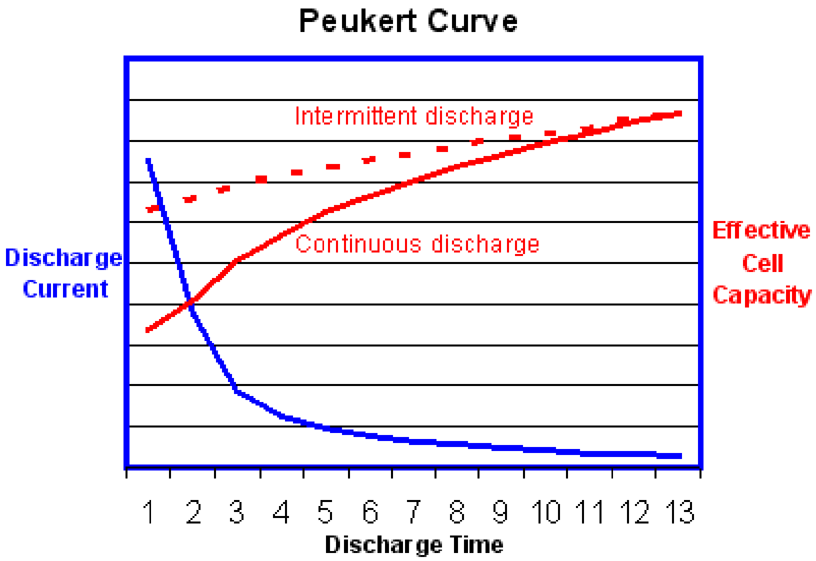
- A typical small electric car will use between 150 to 250 Watthours of energy per mile with normal driving. Thus, for a range of 100 miles at 200 Watthours per mile, a battery capacity of 20 KWh will be required.
- Hybrid electric vehicle use smaller batteries but they may be required to operate at very high discharge rates of up to 40C. If the vehicle uses regenerative braking the battery must also accept very high charging rates to be effective. See the section about Capacitors for an example of how this requirement can be accommodated.

Peukert Equation

The Peukert equation is a convenient way of characterising cell behaviour and of quantifying the capacity offset in mathematical terms.

This is an empirical formula which approximates how the available capacity of a battery changes according to the rate of discharge. $C = I^n T$ where "C" is the theoretical capacity of the battery expressed in amp hours, "I" is the current, "T" is time, and "n" is the Peukert Number, a constant for the given battery. The equation shows that at higher currents, there is less available energy in the battery. The Peukert Number is directly related to the internal resistance of the battery. Higher currents mean more losses and less available capacity.

The value of the Peukert number indicates how well a battery performs under continuous heavy currents. A value close to 1 indicates that the battery performs well; the higher the number, the more capacity is lost when the battery is discharged at high currents. The Peukert number of a battery is determined empirically. For Lead acid batteries the number is typically between 1.3 and 1.4



The graph above shows that the effective battery capacity is reduced at very high continuous discharge rates. However with intermittent use the battery has time to recover during quiescent periods when the temperature will also return towards the ambient level. Because of this potential for recovery, the capacity reduction is less and the operating efficiency is greater if the battery is used intermittently as shown by the dotted line.

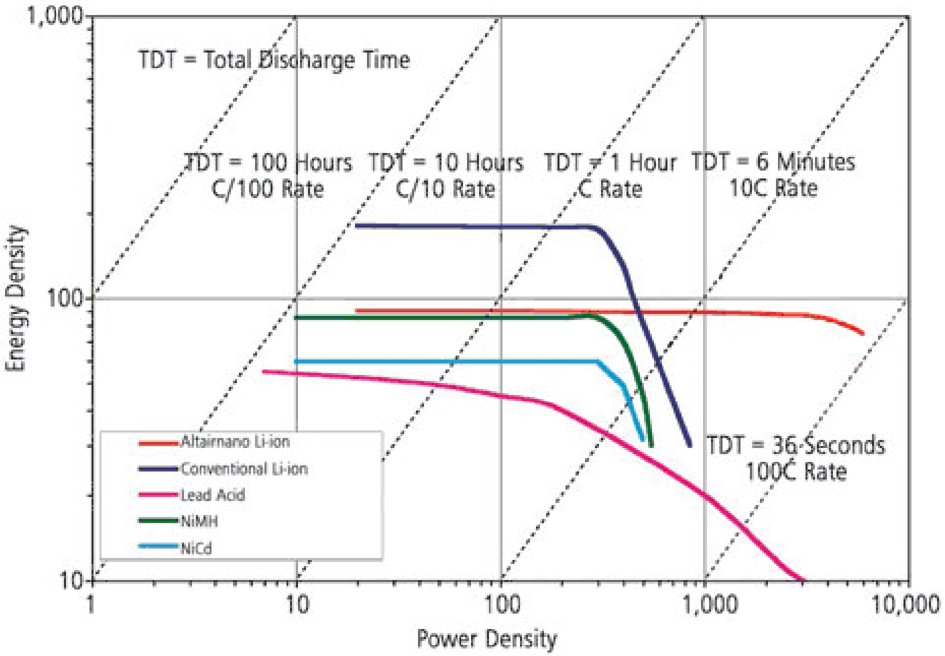
This is the reverse of the behaviour of an internal combustion engine which operates most efficiently with continuous steady loads. In this respect electric power is a better solution for delivery vehicles which are subject to continuous interruptions.

Ragone Plots

The Ragone plot is useful for characterising the trade-off between effective capacity and power handling. Note that the Ragone plots are usually based on logarithmic scales.

The graph below shows the superior gravimetric energy density of Lithium Ion cells. Note also that Lithium ion cells with Lithium Titanate anodes (Altairnano) deliver a very high power density but a ruduced energy density.

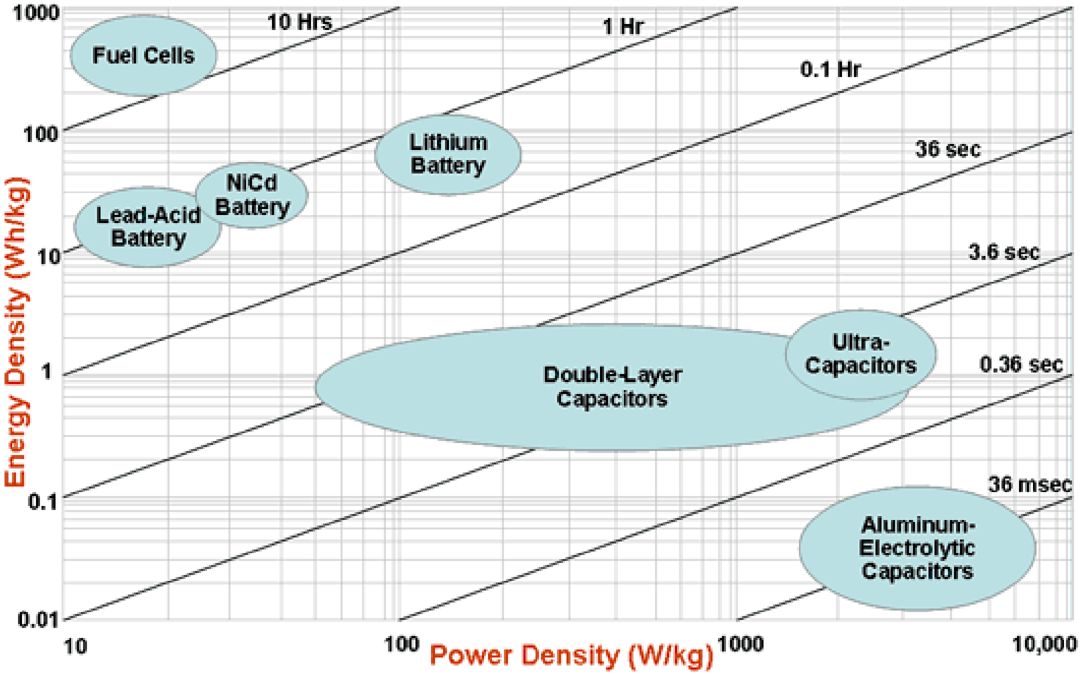
Energy and Power Density - Ragone Plot



Source Altairnano

The Ragone plot below compares the performance of a range of electrochemical devices. It shows that ultracapacitors (supercapacitors) can deliver very high power but the storage capacity is very limited. On the other hand Fuel Cells can store large amounts of energy but have a relatively low power output.

Ragone Plot of Electrochemical Devices



Source US Defence Logistics Agency

The sloping lines on the Ragone plots indicate the relative time to get the charge in or out of the device. At one extreme, power can be pumped into, or extracted from, capacitors in microseconds. This makes them ideal for capturing regenerative braking energy in EV applications. At the other extreme, fuel cells have a very poor dynamic performance taking hours to generate and deliver their energy. This limits their application in EV applications where they are often used in conjunction with batteries or capacitors to overcome this problem. Lithium batteries are somewhere in between and provide a reasonable compromise between the two.

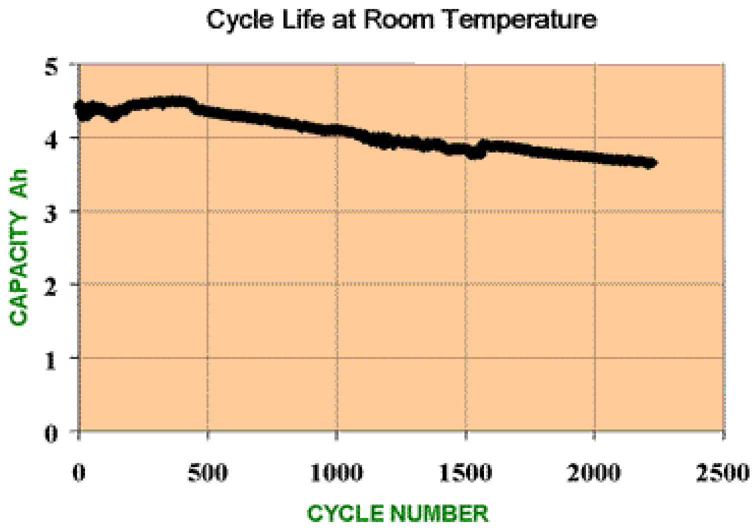
See also Alternative Energy Storage Comparisons.

Pulse Performance

The ability to deliver high current pulses is a requirement of many batteries. The current carrying capacity of a cell depends on the effective surface area of the electrodes. (See Energy/Power Trade-Offs). The current limit is however set by the rate at which the chemical reactions occur within the cell. The chemical reaction or "charge transfer" takes place on the surface of the electrodes and the initial rate can be quite high as the chemicals close to the electrodes are transformed. Once this has occurred however, the reaction rate becomes limited by the rate at which the active chemicals on the electrode surface can be replenished by diffusion through the electrolyte in a process known as "mass transfer". The same principle applies to the charging process and is explained in more detail in the section on Charging Times. The pulse current can therefore be substantially higher than the C rate which characterises the continuous current performance.

Cycle Life

This is one of the key cell performance parameters and gives an indication of the expected working lifetime of the cell.



The cycle life is defined as the number of cycles a cell can perform before its capacity drops to 80% of its initial specified capacity.

Note that the cell does not die suddenly but continues a slow deterioration which will be almost imperceptible to the user. At the end of the specified cycle life the cell will continue to function normally except that its capacity will be significantly less than it was when it was new.

The cycle life as defined is a useful way of comparing batteries under controlled conditions, however it may not give the best indication of battery life under actual operating conditions. Cells are seldom operated under successive, complete charge - discharge cycles, they are much more likely to be subject to partial discharges of varying depth before complete recharging. Since smaller amounts of energy are involved in partial discharges, the battery can sustain a much greater number of shallow cycles. Such usage cycles are typical for Hybrid Electric Vehicle applications with regenerative braking. See how cycle life varies with depth of discharge in Battery Life

A more representative measure of battery life is the **Lifetime Energy Throughput**. This is the total amount of energy in Watthours which can be taken out of a battery over all the cycles in its lifetime before its capacity reduces to 80% of its initial capacity when new. Unfortunately this measure is not yet in common use by cell manufacturers and has not yet been adopted as a battery industry standard. Until it comes into general use it will not be possible to use it to compare the performance of cells from different manufacturers in this way but, when available, at least it provides a more useful guide to applications engineers for estimating the useful life of batteries used in their designs.

Deep Discharge

Cycle life decreases with increased Depth of Discharge (DOD) (See Battery Life) and many cell chemistries will not tolerate deep discharge and cells may be permanently damaged if fully discharged. Special cell constructions and chemical mixes are required to maximise the potential DOD of deep cycle batteries.

Charging Characteristics

Charging curves and recommended charging methods are included in a separate section on Charging

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Lead Acid Batteries

Characteristics

Lead acid batteries were invented in 1859 by Gaston Planté and first demonstrated to the French Academy of Sciences in 1860. They remain the technology of choice for automotive SLI (Starting, Lighting and Ignition) applications because they are robust, tolerant to abuse, tried and tested and because of their low cost. For higher power applications with intermittent loads however, Lead acid batteries are generally too big and heavy and they suffer from a shorter cycle life and typical usable power down to only 50% Depth of Discharge (DOD). Despite these shortcomings Lead acid batteries are still being specified for PowerNet applications (36 Volts 2 kWh capacity) because of the cost, but this is probably the limit of their applicability and NiMH and Li-Ion batteries are making inroads into this market. For higher voltages and cyclic loads other technologies are being explored.

Lead-acid batteries are composed of a Lead-dioxide cathode, a sponge metallic Lead anode and a Sulphuric acid solution electrolyte. This heavy metal element makes them toxic and improper disposal can be hazardous to the environment.

The cell voltage is 2 Volts

Discharge

During discharge, the lead dioxide (positive plate) and lead (negative plate) react with the electrolyte of sulfuric acid to create lead sulfate, water and energy.

Charge

During charging, the cycle is reversed: the lead sulfate and water are electro-chemically converted to lead, lead oxide and sulfuric acid by an external electrical charging source.

Many new competitive cell chemistries are being developed to meet the requirements of the auto industry for EV and HEV applications.

Even after 140 years since its invention, improvements are still being made to the lead acid battery and despite its shortcomings and the competition from newer cell chemistries the lead acid battery still retains the lion's share of the high power battery market.

Advantages

Low cost.

Reliable. Over 140 years of development.

Robust. Tolerant to abuse.

Tolerant to overcharging.

Low internal impedance.

Can deliver very high currents.

Indefinite shelf life if stored without electrolyte.

Can be left on trickle or float charge for prolonged periods.

Wide range of sizes and capacities available.

Many suppliers world wide.

The world's most recycled product.

Shortcomings

Very heavy and bulky.

Typical coulombic charge efficiency only 70% but can be as high as 85% to 90% for special designs.

Danger of overheating during charging

Not suitable for fast charging

Typical cycle life 300 to 500 cycles .

Must be stored in a charged state once the electrolyte has been introduced to avoid deterioration of the active chemicals.

Gassing is the production and release of bubbles of hydrogen and oxygen in the electrolyte during the charging process, particularly due to excessive charging, causing loss of electrolyte. In large battery installations this can cause an explosive atmosphere in the battery room. Sealed batteries are designed to retain and recombine these gases. (See VRLA below)

Sulphation may occur if a battery is stored for prolonged periods in a completely discharged state or very low state of charge, or if it is never fully charged, or if electrolyte has become abnormally low due to excessive water loss from overcharging and/or evaporation. Sulphation is the increase in internal resistance of the battery due to the formation of large lead sulphate crystals which are not readily reconverted back to lead, lead dioxide and sulphuric acid during re-charging. In extreme cases the large crystals may cause distortion and shorting of the plates. Sometimes sulphation can be corrected by charging very slowly (at low current) at a higher than normal voltage.

Completely discharging the battery may cause irreparable damage.

Shedding or loss of material from the plates may occur due to excessive charge rates or excessive cycling. The result is chunks of lead on the bottom of the cell, and actual holes in the plates for which there is no cure. This is more likely to occur in SLI batteries whose plates are composed of a Lead "sponge", similar in appearance to a very fine foam sponge. This gives a very large surface area enabling high power handling, but if deep cycled, this sponge will quickly be consumed and fall to the bottom of the cells.

Toxic chemicals

Very heavy and bulky

Lower temperature limit -15 °C

Decomposition of the Electrolyte Cells with gelled electrolyte are prone to deterioration of the electrolyte and unexpected failure. Such cells are commonly used for emergency applications such as UPS back up in case of loss of mains power. So as not to be caught unawares by an unreliable battery in an emergency situation, it is advisable to incorporate some form of regular self test into the battery.

Charging

Charge immediately after use.

Lasts longer with partial discharges.

Charging method: constant voltage followed by float charge.

Fast charge not possible but charging time can be reduced using the V Taper charge control method.

Applications

Automotive and traction applications.

Standby/Back-up/Emergency power for electrical installations.

Submarines

UPS (Uninterruptible Power Supplies)

Lighting

High current drain applications.

Sealed battery types available for use in portable equipment.

Costs

Low cost

Flooded lead acid cells are one of the least expensive sources of battery power available.

Deep cycle cells may cost up to double the price of the equivalent flooded cells.

Varieties of Lead Acid Batteries

Lead Calcium Batteries

Lead acid batteries with electrodes modified by the addition of Calcium providing the following advantages:

- More resistant to corrosion, overcharging, gassing, water usage, and self-discharge, all of which shorten battery life.
- Larger electrolyte reserve area above the plates.
- Higher Cold Cranking Amp ratings.
- Little or No maintenance.

Lead Antimony Batteries

Lead acid batteries with electrodes modified by the addition of Antimony providing the following advantages:

- Improved mechanical strength of electrodes - important for EV and deep discharge applications
- Reduced internal heat and water loss.
- Longer service life than Calcium batteries.
- Easier to recharge when completely discharged.
- Lower cost.

Lead Antimony batteries have a higher self discharge rate of 2% to 10% per week compared with the 1% to 5% per month for Lead Calcium batteries.

Valve Regulated Lead Acid (VRLA) Batteries

Also called Sealed Lead Acid (**SLA**) batteries.

This construction is designed to prevent electrolyte loss through evaporation, spillage and gassing and this in turn prolongs the life of the battery and eases maintenance. Instead of simple vent caps on the cells to let gas escape, VRLA have pressure valves that open only under extreme conditions. Valve-regulated batteries also need an electrolyte design that reduces gassing by impeding the release to the atmosphere of the oxygen and hydrogen generated by the galvanic action of the battery during charging. This usually involves a catalyst that causes the hydrogen and oxygen to recombine into water and is called a recombinant system. Because spillage of the acid electrolyte is eliminated the batteries are also safer.

AGM Absorbed Glass Mat Battery

Also known as Absorptive Glass Micro-Fibre

Used in VRLA batteries the Boron Silicate fibreglass mat which acts as the separator between the electrodes and absorbs the free electrolyte acting like a sponge. Its purpose is to promote recombination of the hydrogen and oxygen given off during the charging process. No silica gel is necessary. The fibreglass matt absorbs and immobilises the acid in the matt but keeps it in a liquid rather than a gel form. In this way the acid is more readily available to the plates allowing faster reactions between the acid and the plate material allowing higher charge/discharge rates as well as deep cycling.

This construction is very robust and able to withstand severe shock and vibration and the cells will not leak even if the case is cracked.

AGM batteries are also sometimes called "starved electrolyte" or "dry", because the fibreglass mat is only 95% saturated with Sulfuric acid and there is no excess liquid.

Nearly all AGM batteries are sealed valve regulated "VRLA".

AGM's have a very low self-discharge rate of from 1% to 3% per month

Gel Cell

This is an alternative recombinant technology to also used in VRLA batteries to promote recombination of the gases produced during charging. It also reduces the possibility of spillage of the electrolyte. Prone to damage if gassing is allowed to occur, hence charging rates may be limited. They must be charged at a slower rate (C/20) to prevent excess gas from damaging the cells. They cannot be fast charged on a conventional automotive charger or they may be permanently damaged.

Used for UPS applications.

SLI Batteries (Starting Lighting and Ignition)

This is the typical automotive battery application. Automotive batteries are designed to be fully charged when starting the car; after starting the vehicle, the lost charge, typically 2% to 5% of the charge, is replaced by the alternator and the battery remains fully charged. These batteries are not designed to be discharged below 50% Depth of Discharge (DOD) and discharging below these levels can damage the plates and shorten battery life.

Deep Cycle Batteries

Marine applications, golf buggies, fork lift trucks and electric vehicles use deep cycle batteries which are designed to be completely discharged before recharging. Because charging causes excessive heat which can warp the plates, thicker and stronger or solid plate grids are used for deep cycling applications. Normal automotive batteries are not designed for repeated deep cycling and use thinner plates with a greater surface area to achieve high current carrying capacity.

Automotive batteries will generally fail after 30-150 deep cycles if deep cycled, while they may last for thousands of cycles in normal starting use (2-5% discharge).

If batteries designed for deep cycling are used for automotive applications they must be "oversized" by about 20% to compensate for their lower current carrying capacity.

Lead Acid Battery Safety Warning

Source: BCI (Battery Council International)

[History]

Cell Chemistry [Comparison Chart]

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Chargers and Charging

More batteries are damaged by bad charging techniques than all other causes combined.

Charging Schemes

The charger has three key functions

- Getting the charge into the battery (Charging)
- Optimising the charging rate (Stabilising)
- Knowing when to stop (Terminating)

The charging scheme is a combination of the charging and termination methods.

Charge Termination

Once a battery is fully charged, the charging current has to be dissipated somehow. The result is the generation of heat and gasses both of which are bad for batteries. The essence of good charging is to be able to detect when the reconstitution of the active chemicals is complete and to stop the charging process before any damage is done while at all times maintaining the cell temperature within its safe limits. Detecting this cut off point and terminating the charge is critical in preserving battery life. In the simplest of chargers this is when a predetermined upper voltage limit, often called the **termination voltage** has been reached. This is particularly important with fast chargers where the danger of overcharging is greater.

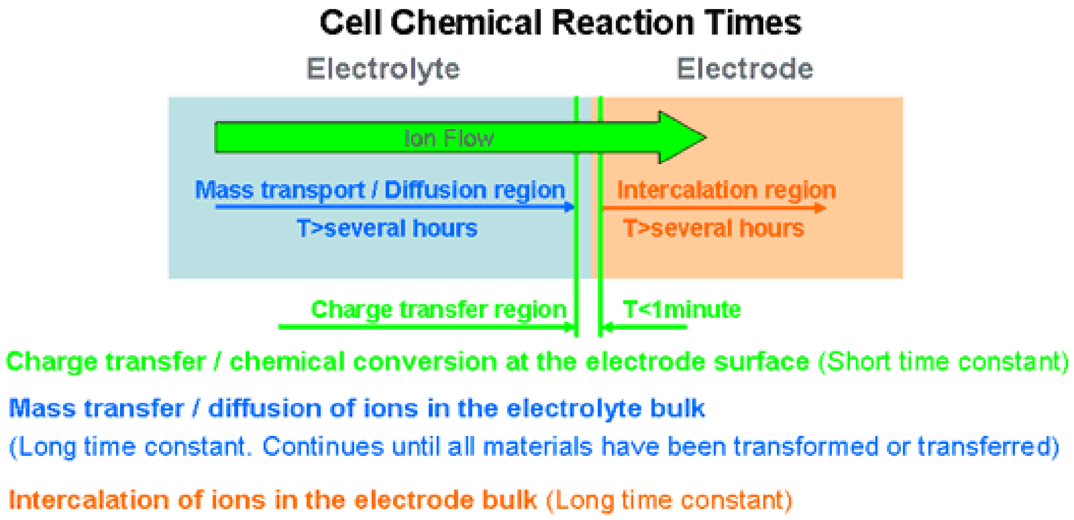
Safe Charging

If for any reason there is a risk of over charging the battery, either from errors in determining the cut off point or from abuse this will normally be accompanied by a rise in temperature. Internal fault conditions within the battery or high ambient temperatures can also take a battery beyond its safe operating temperature limits. Elevated temperatures hasten the death of batteries and monitoring the cell temperature is a good way of detecting signs of trouble from a variety of causes. The temperature signal, or a resettable fuse, can be used to turn off or disconnect the charger when danger signs appear to avoid damaging the battery. This simple additional safety precaution is particularly important for high power batteries where the consequences of failure can be both serious and expensive.

Charging Times

During fast charging it is possible to pump electrical energy into the battery faster than the chemical process can react to it, with damaging results.

The chemical action can not take place instantaneously and there will be a reaction gradient in the bulk of the electrolyte between the electrodes with the electrolyte nearest to the electrodes being converted or "charged" before the electrolyte further away. This is particularly noticeable in high capacity cells which contain a large volume of electrolyte.



There are in fact at least three key processes involved in the cell chemical conversions.

- One is the "charge transfer", which is the actual chemical reaction taking place at the interface of the electrode with the electrolyte and this proceeds relatively quickly.
- The second is the "mass transport" or "diffusion" process in which the materials transformed in the charge transfer process are moved on from the electrode surface, making way for further materials to reach the electrode to take part in the transformation process. This is a relatively slow process which continues until all the materials have been transformed.
- The charging process may also be subject to other significant effects whose reaction time should also be taken into account such as the "intercalation process" by which Lithium cells are charged in which Lithium ions are inserted into the crystal lattice of the host electrode.

All of these processes are also temperature dependent.

In addition there may be other parasitic or side effects such as passivation of the electrodes, crystal formation and gas build up, which all affect charging times and efficiencies, but these may be relatively minor or infrequent, or may occur only during conditions of abuse. They are therefore not considered here.

The battery charging process thus has at least three characteristic time constants associated with achieving complete conversion of the active chemicals which depend on both the chemicals employed and on the cell construction. The time constant associated with the charge transfer could be one minute or less, whereas the mass transport time constant can be as high as several hours or more in a large high capacity cell. This is one of the the reasons why cells can deliver or accept very high pulse currents, but much lower continuous currents.(Another major factor is the heat dissipation involved). These phenomena are non linear and apply to the discharging process as well as to charging. There is thus a limit to the charge acceptance rate of the cell. Continuing to pump energy into the cell faster than the chemicals can react to the charge can cause local overcharge conditions including polarisation, overheating as well as unwanted chemical reactions, near to the electrodes thus damaging the cell. Fast charging forces up the rate of chemical reaction in the cell (as does fast discharging) and it may be necessary to allow "rest periods" during the charging process for the chemical actions to propagate throughout the bulk of the chemical mass in the cell and to stabilise at progressive levels of charge.

A memorable though not quite equivalent phenomenon is the pouring of beer into a glass. Pouring very quickly results in a lot of froth and a small amount of beer at the bottom of the glass. Pouring slowly down the side of the glass or alternatively letting the beer settle till the froth disperses and then topping up allows the glass to be filled completely.

Hysteresis

The time constants and the phenomena mentioned above thus give rise to hysteresis in the battery. During charging the chemical reaction lags behind the application of the charging voltage and similarly, when a load is applied to the battery to discharge it, there is a delay before the full current can be delivered through the load. As with magnetic hysteresis, energy is lost during the charge discharge cycle due to the chemical hysteresis effect.

Fast charging also causes increased Joule heating of the cell because of the higher currents involved and the higher temperature in turn causes an increase in the rate of the chemical conversion processes.

The section on Discharge Rates shows how the effective cell capacity is affected by the discharge rates.
The section on Cell Construction describes how the cell designs can be optimised for fast charging.

Charge Efficiency

This refers to the properties of the battery itself and does not depend on the charger. It is the ratio (expressed as a percentage) between the energy removed from a battery during discharge compared with the energy used during charging to restore the original capacity. Also called the Coulombic Efficiency or Charge Acceptance.

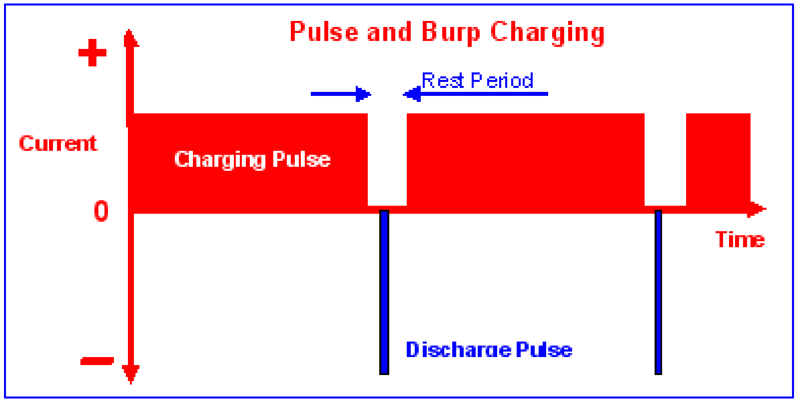
Charge acceptance and charge time are considerably influenced by temperature as noted above. Lower temperature increases charge time and reduces charge acceptance.

Note that at low temperatures the battery will not necessarily receive a full charge even though the terminal voltage may indicate full charge. See

Factors Influencing State of Charge.

Basic Charging Methods

- **Constant Voltage** A constant voltage charger is basically a DC power supply which in its simplest form may consist of a step down transformer from the mains with a rectifier to provide the DC voltage to charge the battery. Such simple designs are often found in cheap car battery chargers. The lead-acid cells used for cars and backup power systems typically use constant voltage chargers. In addition, lithium-ion cells often use constant voltage systems, although these usually are more complex with added circuitry to protect both the batteries and the user safety.
- **Constant Current** Constant current chargers vary the voltage they apply to the battery to maintain a constant current flow, switching off when the voltage reaches the level of a full charge. This design is usually used for nickel-cadmium and nickel-metal hydride cells or batteries.
- **Taper Current** This is charging from a crude unregulated constant voltage source. It is not a controlled charge as in V Taper above. The current diminishes as the cell voltage (back emf) builds up. There is a serious danger of damaging the cells through overcharging. To avoid this the charging rate and duration should be limited. Suitable for SLA batteries only.
- **Pulsed charge** Pulsed chargers feed the charge current to the battery in pulses. The charging rate (based on the average current) can be precisely controlled by varying the width of the pulses, typically about one second. During the charging process, short rest periods of 20 to 30 milliseconds, between pulses allow the chemical actions in the battery to stabilise by equalising the reaction throughout the bulk of the electrode before recommencing the charge. This enables the chemical reaction to keep pace with the rate of inputting the electrical energy. It is also claimed that this method can reduce unwanted chemical reactions at the electrode surface such as gas formation, crystal growth and passivation. (See also Pulsed Charger below). If required, it is also possible to sample the open circuit voltage of the battery during the rest period.



The optimum current profile depends on the cell chemistry and construction.

- **Burp charging** Also called **Reflex** or **Negative Pulse Charging** Used in conjunction with pulse charging, it applies a very short discharge pulse, typically 2 to 3 times the charging current for 5 milliseconds, during the charging rest period to depolarise the cell. These pulses dislodge any gas bubbles which have built up on the electrodes during fast charging, speeding up the stabilisation process and hence the overall charging process. The release and diffusion of the gas bubbles is known as "burping". Controversial claims have been made for the improvements in both the charge rate and the battery lifetime as well as for the removal of dendrites made possible by this technique. The least that can be said is that "it does not damage the battery".

- **IUI Charging** This is a recently developed charging profile used for fast charging standard flooded lead acid batteries from particular manufacturers. It is not suitable for all lead acid batteries. Initially the battery is charged at a constant (I) rate until the cell voltage reaches a preset value - normally a voltage near to that at which gassing occurs. This first part of the charging cycle is known as the bulk charge phase. When the preset voltage has been reached, the charger switches into the constant voltage (U) phase and the current drawn by the battery will gradually drop until it reaches another preset level. This second part of the cycle completes the normal charging of the battery at a slowly diminishing rate. Finally the charger switches again into the constant current mode (I) and the voltage continues to rise up to a new higher preset limit when the charger is switched off. This last phase is used to equalise the charge on the individual cells in the battery to maximise battery life. See Cell Balancing.
- **Trickle charge** Trickle charging is designed to compensate for the self discharge of the battery. Continuous charge. Long term constant current charging for standby use. The charge rate varies according to the frequency of discharge. Not suitable for some battery chemistries, e.g. NiMH and Lithium, which are susceptible to damage from overcharging. In some applications the charger is designed to switch to trickle charging when the battery is fully charged.
- **Float charge**. The battery and the load are permanently connected in parallel across the DC charging source and held at a constant voltage below the battery's upper voltage limit. Used for emergency power back up systems. Mainly used with lead acid batteries.
- **Random charging** All of the above applications involve controlled charge of the battery, however there are many applications where the energy to charge the battery is only available, or is delivered, in some random, uncontrolled way. This applies to automotive applications where the energy depends on the engine speed which is continuously changing. The problem is more acute in EV and HEV applications which use regenerative braking since this generates large power spikes during braking which the battery must absorb. More benign applications are in solar panel installations which can only be charged when the sun is shining. These all require special techniques to limit the charging current or voltage to levels which the battery can tolerate.

Charging Rates

Batteries can be charged at different rates depending on the requirement. Typical rates are shown below:

- Slow Charge = Overnight or 14-16 hours charging at 0.1C rate
- Quick Charge = 3 to 6 Hours charging at 0.3C rate
- Fast Charge = Less than 1 hour charging at 1.0C rate

Slow charging

Slow charging can be carried out in relatively simple chargers and should not result in the battery overheating. When charging is complete batteries should be removed from the charger.

- Nicads are generally the most robust type with respect to overcharging and can be left on trickle charge for very long periods since their recombination process tends to keep the voltage down to a safe level. The constant recombination keeps internal cell pressure high, so the seals gradually leak. It also keeps the cell temperature above ambient, and higher temperatures shorten life. So life is still better if you take it off the charger.
- Lead acid batteries are slightly less robust but can tolerate a short duration trickle charge. Flooded batteries tend to use up their water, and SLAs tend to die early from grid corrosion. Lead-acids should either be left sitting, or float-charged (held at a constant voltage well below the gassing point).
- NiMH cells on the other hand will be damaged by prolonged trickle charge.
- Lithium ion cells however can not tolerate overcharging or overvoltage and the charge should be terminated immediately when the upper voltage limit is reached.

Fast / Quick Charging

As the charging rate increases, so do the dangers of overcharging or overheating the battery. Preventing the battery from overheating and terminating the charge when the battery reaches full charge become much more critical. Each cell chemistry has its own characteristic charging curve and battery chargers must be designed to detect the end of charge conditions for the specific chemistry involved. In addition, some form of Temperature Cut Off (TCO) or Thermal Fuse must be incorporated to prevent the battery from overheating during the charging process.

Fast charging and quick charging require more complex chargers. Since these chargers must be designed for specific cell chemistries, it is not normally possible to charge one cell type in a charger that was designed for another cell chemistry and damage is likely to occur. Universal chargers, able to charge all cell types, must have sensing devices to identify the cell type and apply the appropriate charging profile.

Note that for automotive batteries the charging time may be limited by the available power rather than the battery characteristics. Domestic 13 Amp ring main circuits can only deliver 3KW. Thus, assuming no efficiency loss in the charger, a ten hour charge will at maximum put 30 KWh of energy into the battery. Enough for about 100 miles. Compare this with filling a car with petrol.
It takes about 3 minutes to put 90 KWh of energy into the tank, sufficient to take the car 300 miles. To put 90 KWh into a battery in 3 minutes would be equivalent to a charging rate of 1.8 MegaWatts!!

Charge Termination Methods

The following chart summarises the charge termination methods for popular batteries. These are explained in the section below.

	Charge Termination Methods			
	SLA	Nicad	NiMH	Li-Ion
Slow Charge	Trickle OK	Tolerates Trickle	Timer	Voltage Limit
Fast Charge 1	Imin	NDV	dT/dt	Imin at Voltage Limit
Fast Charge 2	Delta TCO	dT/dt	dV/dt=0	
Back up Termination 1	Timer	TCO	TCO	TCO
Back up Termination 2	DeltaTCO	Timer	Timer	Timer

TCO = Temperature Cut Off

Delta TCO = Temperature rise above ambient

I min = Minimum current

Charge Control Methods

Many different charging and termination schemes have been developed for different chemistries and different applications. The most common ones are summarised below.

Controlled charging

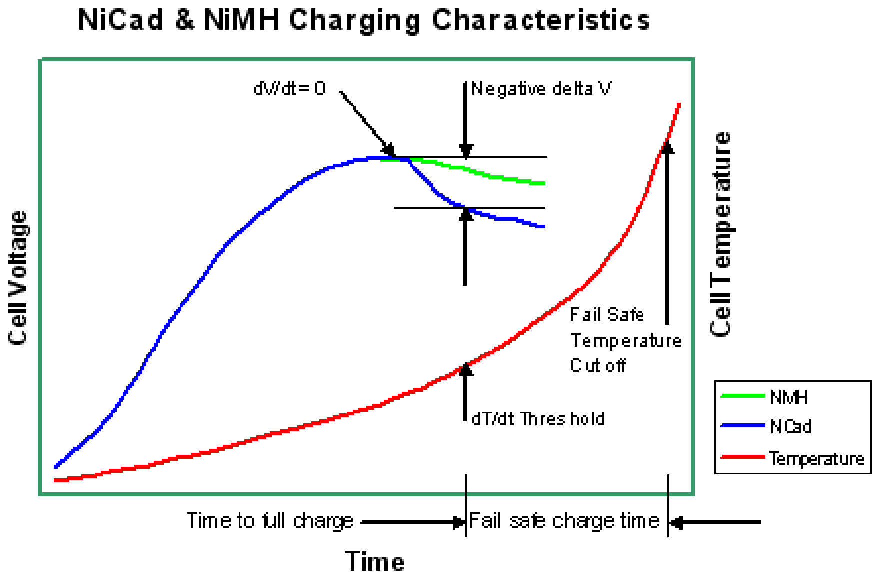
Regular (slow) charge

- **Semi constant current** Simple and economical. Most popular. Low current therefore does not generate heat but is slow, 5 to 15 hours typical. Charge rate 0.1C. Suitable for Nicads
- **Timer controlled** charge system Simple and economical. More reliable than semi-constant current. Uses IC timer. Charges at 0.2C rate for a predetermined period followed by trickle charge of 0.05C. Avoid constantly restarting timer by taking the battery in and out of the charger since this will compromise its effectiveness. The incorporation of an absolute temperature cut-off is recommended. Suitable for Nicad and NiMH batteries.

Fast charge (1 to 2 hours)

- **Negative delta V (NDV) Cut-off charge system**

  This is the most popular method for rapid charging for Nicads.

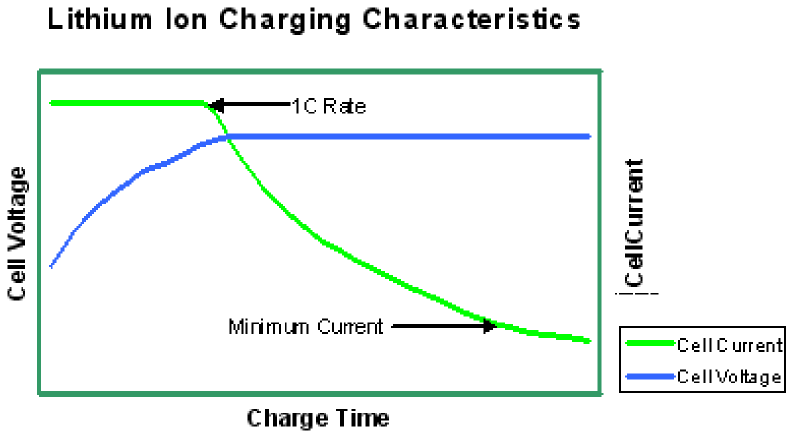


Batteries are charged at constant current of between 0.5 and 1.0 C rate. The battery voltage rises as charging progresses to a peak when fully charged then subsequently falls. This voltage drop, -delta V, is due to polarisation or oxygen build up inside the cell which starts to occur once the cell is fully charged. At this point the cell enters the overcharge danger zone and the temperature begins to rise rapidly since the chemical changes are complete and the excess electrical energy is converted into heat. The voltage drop occurs regardless of the discharge level or ambient temperature and it can therefore be detected and used to identify the peak and hence to cut off the charger when the battery has reached its full charge or switch to trickle charge.

This method is not suitable for charging currents less than 0.5 C since delta V becomes difficult to detect. False delta V can occur at the start of the charge with excessively discharged cells. This is overcome by using a timer to delay the detection of delta V sufficiently to avoid the problem. Lead acid batteries do not demonstrate a voltage drop on charge completion hence this charging method is not suitable for SLA batteries.

- **dT/dt Charge system** NiMH batteries do not demonstrate such a pronounced NDV voltage drop when they reach the end of the charging cycle as can be seen in the graph above and so the NDV cut off method is not reliable for ending the NiMH charge. Instead the charger senses the rate of increase of the cell temperature per unit time. When a predetermined rate is reached the rapid charge is stopped and the charge method is switched to trickle charge. This method is more expensive but avoids overcharge and gives longer life. Because extended trickle charging can damage a NiMH battery, the use of a timer to regulate the total charging time is recommended.

- **Constant-current Constant-voltage controlled** charge system. Used for charging Lithium batteries which are vulnerable to damage if the upper voltage limit is exceeded. Special precautions are needed to ensure the battery is fully charged while at the same time avoiding overcharging. For this reason it is recommended that the charging method switches to constant voltage before the cell voltage reaches its upper limit.



The charge voltage rises rapidly to the cell upper voltage limit and is subsequently maintained at that level. As the charge approaches completion the current decreases to a trickle charge. Cut off occurs when a predetermined minimum current point, which indicates a full charge, has been reached. Used for Lithium and SLA batteries. See also Lithium Batteries - Charging and Battery Manufacturing - Formation.

Note: When **Fast Charging** rates are specified, they usually refer to the constant current period. Depending on the cell chemistry this period could be between 60% and 80% of the time to full charge. These rates should not be extrapolated to estimate the time to fully charge the battery because the charging rate tails off quickly during the constant voltage period.

- **Voltage controlled** charge system. Fast charging at rates between 0.5 and 1.0 C rate. The charger switched off or switched to trickle charge when predetermined voltage has been reached. Should be combined with temperature sensors in the battery to avoid overcharge or thermal runaway.
- **V- Taper controlled** charge system Similar to Voltage controlled system. Once a predetermined voltage has been reached the rapid charge current is progressively reduced by reducing the supply voltage then switched to trickle charge. Suitable for SLA batteries it allows higher charge level to be reached safely. (See also taper current below)
- **Failsafe timer**

  Limits the amount of charge current that can flow to double the cell capacity. For example for a 600mAh cell, limit the charge to a maximum of 1,200mAH. Last resort if cut off not achieved by other means.
- **Intelligent Charging System**

  Intelligent charging systems integrate the control systems within the charger with the electronics within the battery to allow much finer control over the charging process. The benefits are faster and safer charging and battery longer cycle life. Such a system is described in the section on Battery Management Systems.

Note

Most chargers provided with consumer electronics devices such as mobile phones and laptop computers simply provide a fixed voltage source. The required voltage and current profile for charging the battery is provided (or should be provided) from electronic circuits, either within the device itself or within the battery pack, rather than by the charger. This allows flexibility in the choice of chargers and also serves to protect the device from potential damage from the use of inappropriate chargers.

Voltage Sensing

During charging, for simplicity, the battery voltage is usually measured across the charger leads. However for high current chargers, there can be a significant voltage drop along the charger leads, resulting in an underestimate of the true battery voltage and consequent undercharging of the battery if the battery voltage is used as the cut-off trigger. The solution is to measure the voltage using a separate pair of wires connected directly across the battery terminals. Since the voltmeter has a high internal impedance there will be minimal voltage drop in the voltmeter leads and the reading will be more accurate. This method is called a Kelvin Connection. See also DC Testing.

Charger Types

Chargers normally incorporate some form of voltage regulation to control the charging voltage applied to the battery. The choice of charger circuit technology is usually a price - performance trade off. Some examples follow:

- **Switch Mode Regulator (Switcher)** - Uses pulse width modulation to control the voltage. Low power dissipation over wide variations in input and battery voltage. More efficient than linear regulators but more complex.
  Needs a large passive output filter to smooth the pulsed waveform. Component size can be reduced by using higher switching frequency. Switching heavy currents gives rise to EMI and electrical noise.
- **Series Regulator (Linear)** - Less complex but more lossy - requiring a heat sink to dissipate the heat in the series, voltage dropping transistor which takes up the difference between the supply and the output voltage. All the load current passes through the regulating transistor which consequently must be a high power device. Because there is no switching, it delivers pure DC and doesn't need an output filter. For the same reason, the design doesn't suffer from the problem of radiated and conducted emissions and electrical noise. This makes it suitable for low noise wireless and radio applications.
  With fewer components they are also smaller.
- **Shunt Regulator -** Shunt regulators are common in photovoltaic (PV) systems since they are relatively cheap to build and simple to design. The charging current is controlled by a switch or transistor connected in parallel with the photovoltaic panel and the storage battery. Overcharging of the battery is prevented by shorting (shunting) the PV output through the transistor when the voltage reaches a predetermined limit. If the battery voltage exceeds the PV supply voltage the shunt will also protect the PV panel from damage due to reverse voltage by discharging the battery through the shunt. Series regulators usually have better control and charge characteristics.
- **Buck Regulator** A switching regulator which incorporates a step down DC-DC converter. They have high efficiency and low heat losses. They can handle high output currents and generate less RF interference than a conventional switch mode regulator. A simple transformerless

design with low switch stress and a small output filter.

- **Pulsed Charger**. Uses a series transistor which can also be switched. With low battery voltages the transistor remains on and conducts the source current directly to the battery. As the battery voltage approaches the desired regulation voltage the series transistor pulses the input current to maintain the desired voltage. Because it acts as a switch mode supply for part of the cycle it dissipates less heat and because it acts as a linear supply part of the time the output filters can be smaller. Pulsing allows the battery time to stabilise (recover) with low increments of charge at progressively high charge levels during charging. During rest periods the polarisation of the cell is lowered. This process permits faster charging than possible with one prolonged high level charge which could damage the battery since it does not permit gradual stabilisation of the active chemicals during charging. Pulse chargers usually need current limiting on the input source for safety reasons, adding to the cost.
- **Inductive charging**

  Inductive charging does not refer to the charging process of the battery itself. It refers to the design of the charger. Essentially the input side of charger, the part connected to the AC mains power, is constructed from a transformer which is split into two parts. The primary winding of the transformer is housed in a unit connected to the AC mains supply, while the secondary winding of the transformer is housed in the same sealed unit which contains the battery, along with the rest of the conventional charger electronics. This allows the battery to be charged without a physical connection to the mains and without exposing any contacts which could cause an electric shock to the user.

  A low power example is the electric toothbrush. The toothbrush and the charging base form the two-part transformer, with the primary induction coil contained in the base and the secondary induction coil and the electronics contained in the toothbrush. When the toothbrush is placed into the base, the complete transformer is created and the induced current in the secondary coil charges the battery. In use, the appliance is completely separated from the mains power and since the battery unit is contained in a sealed compartment the toothbrush can be safely immersed in water.

  The technique is also used to charge medical battery implants.

  A high power example is a charging system used for EVs. Similar to the toothbrush in concept but on a larger scale, it is also a non-contact system. An induction coil in the electric vehicle picks up current from an induction coil in the floor of the garage and charges the vehicle overnight. To optimise system efficiency, the air gap between the static coil and the pickup coil can be reduced by lowering the pickup coil during charging and the vehicle must be precisely placed over the charging unit.
  A similar system has been used for electric buses which pick up current from induction coils embedded beneath each bus stop thus enabling the range of the bus to be extended or conversely, smaller batteries can be specified for the same itinerary. One other advantage of this system is that if the battery charge is constantly topped up, the depth of discharge can be minimised and this leads to a longer cycle life. As shown in the section on Battery Life, the cycle life increases exponentially as the depth of discharge is reduced.

Charger Power Sources

When specifying a charger it is also necessary to specify the source from which the charger derives its power, its availability and its voltage and power range. Efficiency losses in the charger should also be taken into account, particularly for high power chargers where the magnitude of the losses can be significant. Some examples are given below.

Controlled Charging

Easy to accommodate and manage.

- **AC Mains**

  Many portable low power chargers for small electrical appliances such as computers and mobile phones are required to operate in international markets. They therefore have auto sensing of the mains voltage and in special cases the mains frequency with automatic switching to the appropriate input circuit.

  Higher power applications may need special arrangements. Single phase mains power is typically limited to about 3 KW. Three phase power may be required for charging high capacity batteries (over 20 KWh capacity) such as those used in electric vehicles which may require charging rates of greater than 3 KW to achieve reasonable charging times.
- **Regulated DC Battery Supply**

  May be provided by special purpose installations such as mobile generating equipment for custom applications.
- **Special Chargers**

  Portable sources such as solar panels.

Opportunity Charging

Opportunity charging is charging the battery whenever power is available or between partial discharges rather than waiting for the battery to be completely discharged. It is used with batteries in cycle service, and in applications when energy is available only intermittently.

It can be subject to wide variations in energy availability and wide variations in power levels. Special control electronics are needed to protect the battery from overvoltage. By avoiding complete discharge of the battery, cycle life can be increased.

Availability affects the battery specification as well as the charger.

Typical applications are:-

- **Onboard vehicle chargers** (Alternators, Regenerative braking)
- **Inductive chargers** (on vehicle route stopping points)
- **Solar power**
- **Wind power**

Mechanical charging

This is only applicable to specific cell chemistries. It is nor a charger technology in the normal sense of the word. Mechanical charging is used in some high power batteries such as Flow Batteries and Zinc Air batteries. Zinc air batteries are recharged by replacing the zinc electrodes. Flow batteries can be recharged by replacing the electrolyte.

Mechanical charging can be carried out in minutes. This is much quicker than the the long charging time associated with the conventional reversible cell electrochemistry which could take several hours. Zinc air batteries have therefore been used to power electric buses to overcome the problem of excessive charging times.

Charger Performance

The battery type and the application in which it is used set performance requirements which the charger must meet.

- **Output Voltage Purity**

  The charger should deliver a clean regulated voltage output with tight limits on spikes, ripple, noise and radio frequency interference (RFI) all of which could cause problems for the battery or the circuits in which it is used.

For high power applications, the charging performance may be limited by the design of the charger.

- **Efficiency**

  When charging high power batteries, the energy loss in the charger can add significantly to the charging times and to the operating costs of the application. Typical charger efficiencies are around 90%, hence the need for efficient designs.
- **Inrush Current**

  When a charger is initially switched on to an empty battery the inrush current could be considerably higher than the maximum specified charging current. The charger must therefore be dimensioned either to deliver or limit this current pulse.
- **Power Factor**

  This could also be an important consideration for high power chargers.

See also "Charger Checklist"

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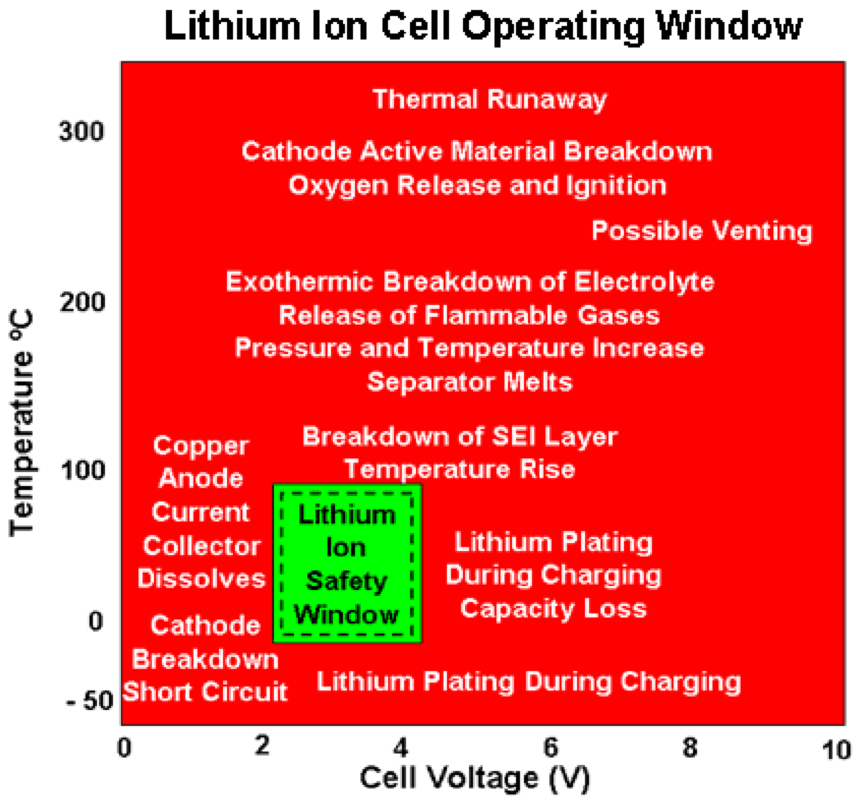
Lithium Battery Failures

The performance of Lithium Ion cells is dependent on both the temperature and the operating voltage. The diagram below shows that, at all times, the cell operating voltage and temperature must be kept within the limits indicated by the green box. Once outside the box permanent damage to the cell will be initiated.

Cell Failures



Voltage Effects

- **Over-Voltage**

  If the charging voltage is increased beyond the recommended upper cell voltage, typically 4.2 Volts, excessive current flows giving rise to two problems.

  - Lithium Plating

  With excessive currents the Lithium ions can not be accommodated quickly enough between the intercalation layers of the anode and Lithium ions accumulate on the surface of the anode where they are deposited as metallic Lithium. This is known as Lithium plating. The consequence is an irreversible capacity loss and ultimately a short circuit between the electrodes.

  - Overheating

    Excessive current also causes increased Joule heating of the cell, accompanied by an increase in temperature. See next section below.

- **Under-voltage / Over-discharge**

  Rechargeable Lithium cells suffer from under-voltage as well as over-voltage. Allowing the cell voltage to fall below about 2 Volts by over-discharging or storage for extended periods results in progressive breakdown of the electrode materials.

  - Anodes

    First the anode copper current collector is dissolved into the electrolyte. This increases the self discharge rate of the cell and can ultimately cause a short circuit between the electrodes.

  - Cathodes

    Keeping the cells for prolonged periods at voltages below 2 Volts results in the gradual breakdown of the cathode over many cycles with the release of Oxygen by the Lithium Cobalt Oxide and Lithium Manganese Oxide cathodes and a consequent permanent capacity loss. With Lithium Iron Phosphate cells this can happen over a few cycles .

Temperature Effects

Heat is a major battery killer, either excess of it or lack of it, and Lithium secondary cells need careful temperature control.

- **Low temperature operation**

  Chemical reaction rates decrease in line with temperature. (Arrhenius Law) The effect of reducing the operating temperature is to reduce rate at which the active chemicals in the cell are transformed. This translates to a reduction in the current carrying capacity of the cell both for charging and discharging. In other words its power handling capacity is reduced. Details of this process are given in the section on Charging Rates

  Futhermore, at low temperatures, the reduced reaction rate (and perhaps contraction of the electrode materials) slows down, and makes makes more difficult, the insertion of the Lithium ions into the intercallation spaces. As with over-voltage operation, when the electrodes can not accomodate the current flow, the result is reduced power and anode plating with irreversible capacity loss.

- **High temperature operation**

  Operating at high temperatures brings on a different set of problems which can result in the destruction of the cell. In this case, the Arrhenius effect helps to get higher power out of the cell by increasing the reaction rate, but higher currents give rise to higher I^2R heat dissipation and thus even higher temperatures. This can be the start of positive temperature feedback and unless heat is removed faster than it is generated the result will be thermal runaway.

- **Thermal runaway**

Several stages are involved in the build up to thermal runaway and each one results in progressively more permanenet damage to the cell.

- The first stage is the breakdown of the thin passivating SEI layer on the anode, due to overheating or physical penetration. The initial overheating may be caused by excessive currents, overcharging or high external ambient temperature.The breakdown of the SEI layer starts at the relatively low temperature of 80ºC and once this layer is breached the electrolyte reacts with the carbon anode just as it did during the formation process but at a higher, uncontrolled, temperature. This is an exothermal reaction which drives the temperature up still further.

  (Lithium Titanate anodes do not depend on an SEI layer and hence can be used at higher rates.)
- As the temperature builds up, heat from anode reaction causes the breakdown of the organic solvents used in the electrolyte releasing flammable hydrocarbon gases (Ethane, Methane and others) but no Oxygen. This typically starts at 110 ºC but with some electrolytes it can be as as low as 70ºC. The gas generation due to the breakdown of the electrolyte causes pressure to build up inside the cell. Although the temperature increases to beyond the flashpoint of the gases released by the electrolyte the gases do not burn because there is no free Oxygen in the cell to sustain a fire.

  The cells are normally fitted with a safety vent which allows the controlled release of the gases to relieve the internal pressure in the cell avoiding the possibility of an uncontrolled rupture of the cell - otherwise known as an explosion or more euphemistically "rapid disassembly" of the cell. Once the hot gases are released to the atmosphere they can of course burn in the air.
- At around 135 ºC the polymer separator melts, allowing the short circuits between the electrodes.
- Eventually heat from the electrolyte breakdown causes breakdown of the metal oxide cathode material releasing Oxygen which enables burning of both the electrolyte and the gases inside the cell.

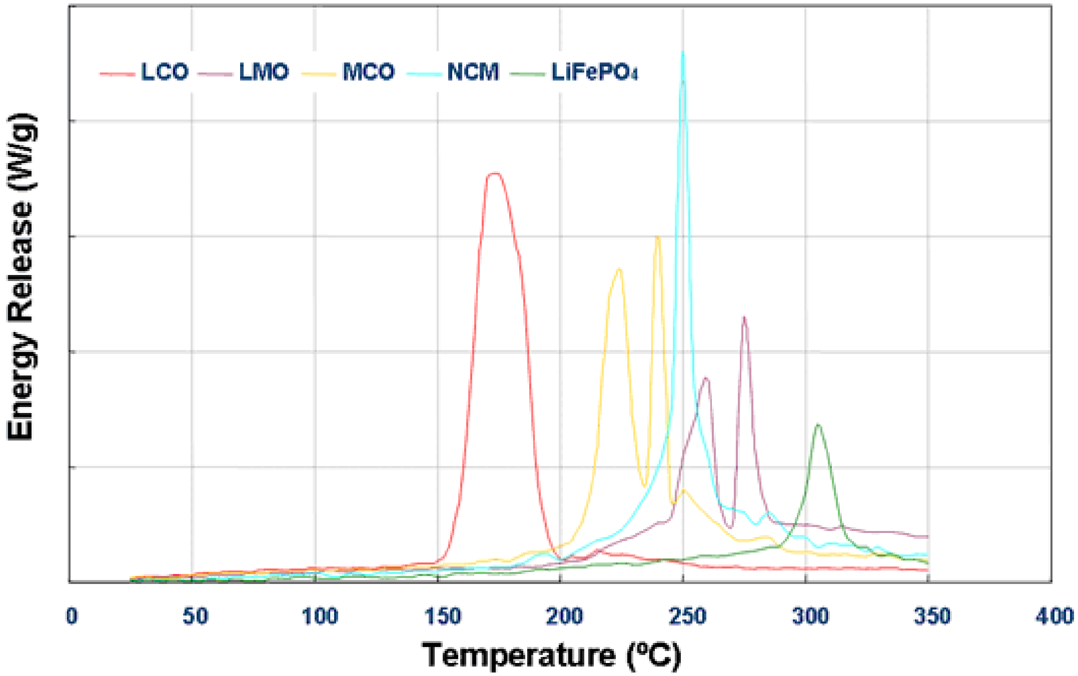
  The breakdown of the cathode is also highly exothermic sending the temperature and pressure even higher. The cathode breakdown starts at around 200 ºC for Lithium Cobalt Oxide cells but at higher temperatures for other cathode chemistries.

  By this time the pressure is also extremely high and it's time to run for the door.

See methods used to avoid these problems in the section on Cell Protection

Alternative Lithium cathode chemistries

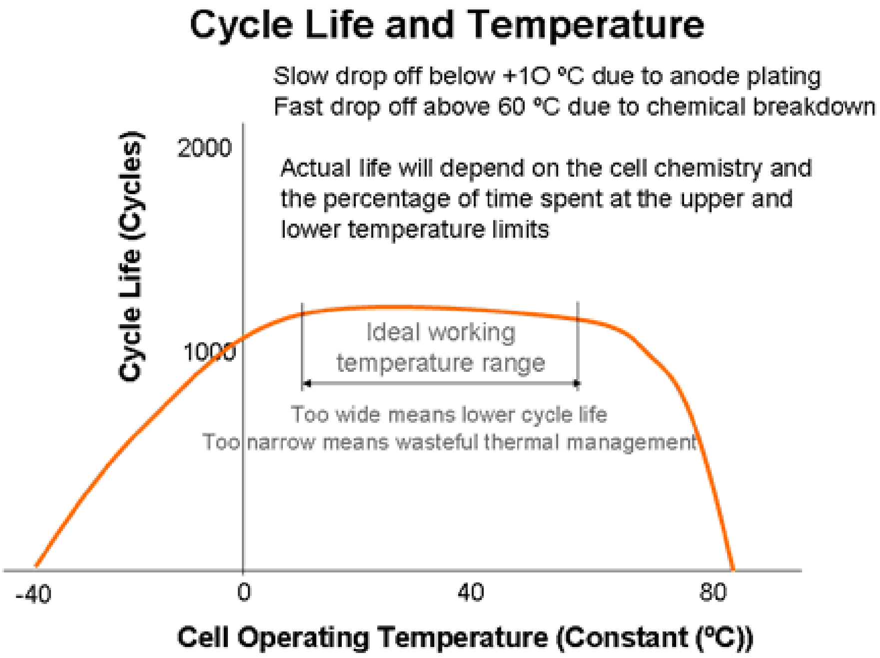
Lithium Cobalt Oxide was the first material used for the cathodes in Lithium secondary cells but safety concerns were raised for two reasons. The onset of chemical breakdown is at a relatively low temperature and when the cathode breaks down, prodigious amounts of energy are released. For that reason alternative cathode materials have been developed. The diagram below shows the breakdown characteristics of several alternative cathode materials.



The graph above shows that Lithium Iron Phosphate cathodes do not break down with the release of oxygen until much higher temperatures and when they do, much less energy is released. The reason is that the Oxygen molecules in the Phosphate material have a much stronger valence bond to the Phosphorus and this is more difficult to break. The other cathode chemistries are based on Lithium metal oxides which have much weaker valence bonds binding the Oxygen to the metal and these are more easily broken to release the Oxygen.

Cycle Life

The effects of voltage and temperature on cell failures tend to be immdiately apparent, but their effect on cycle life is less obvious. We have seen above that excusions outside of the recommended operating window can cause irreversible capacity loss in the cells. The cumulative effect of these digressions is like having a progessively debilitating disease which affects the life time of the cell or in the worst case causes sudden death if you overstep the mark..



The graph above shows that starting at about 15 ºC cycle life will be progressively reduced by working at lower temperatures. Operating slightly above 50 ºC also reduces cycle life but by 70 ºC the threat is thermal runaway. The battery thermal management system must be designed keep the cell operating within its sweet spot at all times to avoid premature wear out of the cells.

Beware: the cycle life quoted in manufacturers' specification sheets normally assumes operating at room temperature. This would be totally unrealistic for automotive applications. Graphs like the one above are seldom provided by cell manufacturers.

Battery Management System (BMS)

One of the main functions of the BMS is to keep the cells operating within their designed operating window (the green box above). This is not too difficult to achieve using safety devices and thermal management systems. As an additional safety factor some manufacturers set their operating limits to more restricted levels indicated by the dotted lines.

There is however very little te BMS can do to protect aginst an internal short circuit. The only prevention action that can be taken is strict process control of all the cell manufacturing operations.

Lithium Charged but Not Guilty?

The cause of many fires has been attributed to Lithium batteries and there is a fear of Lithium because of its well known vigorous reaction with water. Under normal circumstances, most (but not all) batteries do not contain any free Lithium. The Lithium content is combined into other compounds which do not react with water. The amount of Lithium deposited during the Lithium plating when cells are damaged as described above is very small and not usually responsible for the fires which have occurred. Furthermore, many of the reported fires are due to burning electrolyte rather than the Lithium compounds.

The guilty party

Although investigation has shown that some Lithium fires are due to internal short circuits as described above, many, if not most fires are caused by abuse by the user. This may be "deliberate or negligent" abuse such as overcharging or operating in a high temperature environment or physical damage due to mishandling, but quite often it is unconscious abuse. Surprisingly many of the most serious fires have been initiated by inadvertent short circuits caused by careless disposal of cells in the rubbish. While strict regulations for transporting Lithium batteries by air have been implemeted, the sources of several aircraft / transport fires have been identified as spare laptop batteries being carried in passenger luggage shorting against other items packed with them.

Note: Large batteries such as those used in automotive applications usually incorporate short circuit protection, but smaller laptop batteries do not usually have this facility.

See also more general Battery Failure Modes

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Battery Protection Methods

Cell Protection

The purpose of cell protection is to provide the necessary monitoring and control to protect the cells from out of tolerance ambient or operating conditions and to protect the user from the consequences of battery failures. Cell protection can be external to the battery and this is one of the of the prime functions of the Battery Management System.

Safety measures can also be built into the cells themselves and examples are outlined in the section on Battery Safety.

High power cells can be particularly dangerous. They contain large amounts of energy which, if released in an uncontrolled way through a short circuit or physical damage, can have catastrophic consequences. In the case of short circuits, currents of hundreds of amps can build up in microseconds and protection circuits must be very fast acting to prevent this.

Different applications and different cell chemistries require different degrees of protection. Lithium batteries in particular need special protection and control circuits to keep them within their predefined voltage, current and temperature operating limits. Furthermore, the consequences of failure of a Lithium cell could be quite serious, possibly resulting in an explosion or fire. Cell protection is therefore indispensable in Lithium batteries. The following discussion illustrates some of the principles involved.

In general cell protection should address the following undesirable events or conditions:

- Excessive current during charging or discharging.
- Short circuit
- Over voltage - Overcharging
- Under voltage - Exceeding preset depth of discharge (DOD) limits
- High ambient temperature
- Overheating - Exceeding the cell temperature limit
- Pressure build up inside the cell
- System isolation in case of an accident
- Abuse

The two diagrams below illustrate how safety devices are specified to protect the cells from out of tolerance conditions by constraining the cells to a safe working zone.

The red areas are specified by the cell manufacturers as "No go" areas where cells will most likely be subject to permanent damage. Theoretically the cell could work in any of the remaining operating space, however this allows no margin of error and in practice protection devices limit the cells operating conditions to a smaller "safe" operating zone shown here in green. The white area between the safe zone and the failure zone represents the design safety margin.

The diagrams also illustrate how the multiple levels of protection function to ensure safe operating conditions at all times even if one of the devices fails.

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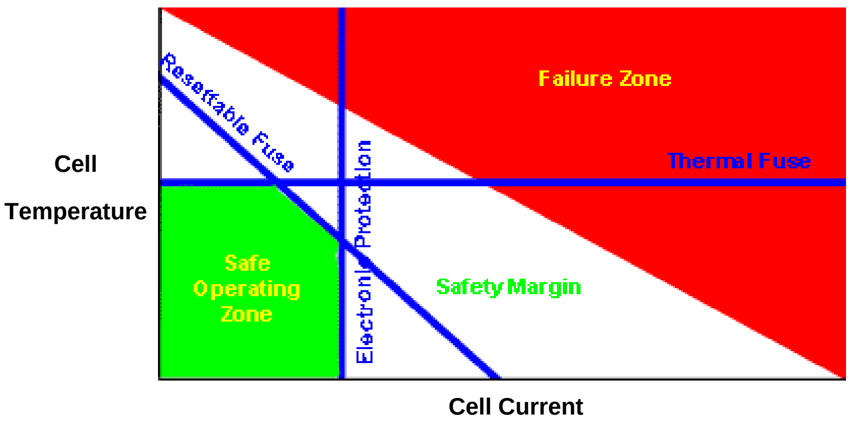
Current Protection



The above diagram shows three protection schemes providing two levels of protection from both over-current and over temperature. If one fails the other one is there as a safety net.

Thermal Fuse

Excessive temperatures will cause all cells to fail eventually. Most protection circuits therefore incorporate a thermal fuse which will permanently shut down the battery if its temperature exceeds a predetermined limit.

Thermistor (Not shown in the diagram)

Thermistors are circuit devices whose resistance varies with temperature. PTC thermistors have a Positive Temperature Coefficient in that their resistance increases gradually with temperature and over a limited range the resistance can be considered linearly proportional to temperature.

Similarly NTC thermistors have a Negative Temperature Coefficient and their resistance decreases as temperature increases. These components are used extensively in monitoring and protection circuits to provide a voltage analogue of temperature or in control circuits designed to provide temperature compensation. They may be used to terminate the charge (dt/dT) or to disconnect the battery from the charger in an over-temperature condition when the temperature cut off point is reached, or they could be used to turn on cooling fans.
In some applications the thermistor may be the only means of communication between the battery and the external world.

Thermistors can also be used by the charger to determine starting environmental conditions and prevent charging if the battery temperature is too low or too high.

Resettable Fuse

A resettable fuse indicated in the diagram above provides on-battery over-current protection. It has a similar function to a thermal fuse but after opening it will reset once the fault conditions have been removed and after it has cooled down again to its normal state. It requires no manual resetting or replacement and so is very convenient for the user who may not even be aware of its operation.
The fuse is triggered when a particular temperature is reached. The temperature rise can be caused by the resistive self heating of the thermistor due to the current passing through it, or by conduction or convection from the ambient environment. Thus it can be used to protect against both over- current and over-temperature.

Also called a PPTC (Polymeric Positive Temperature Coefficient) device, the resettable fuse is a non-linear PTC thermistor based on a thin composite of semi crystalline polymer and conductive particles. Under normal operating conditions, the conductive particles provide a low resistance path allowing current to flow. Under fault conditions that cause excessive temperature, such as excessive current flow or an excessively high ambient temperature, the crystallites in the polymer undergo an abrupt phase change within a very narrow temperature range melting and becoming amorphous causing separation of the particles resulting in a large, non-linear increase in resistance.
The sharp increase in resistance is typically three orders of magnitude or more, reducing the current to a relatively low and safe level. It will hold in this high resistance state until the fault conditions are removed. On cooling the phase change is reversed and the PPTC resets to low resistance state (within certain post trip limits).

Devices have a de-rating at elevated temperatures which means that they will trip at a lower current if the temperature is higher. Environmental and electrical details of application must be full understood when designing in resettable fuse protection.
These devices are easily integrated into battery design by welding across cell terminals or placing on circuit board.

The "Polyswitch" is an example of such a device. (Polyswitch™ is a trademark of Raychem corp.)

Fuses

Conventional fuses may be used to protect the battery from an overload, but in many situations they may not act quickly enough. This is particularly true if the battery is short circuited. Since the battery has a very low internal impedance, very high instantaneous currents can flow which can seriously damage the battery. Fuses however are very slow to operate in fault conditions and may not act quickly enough if the battery is short circuited.

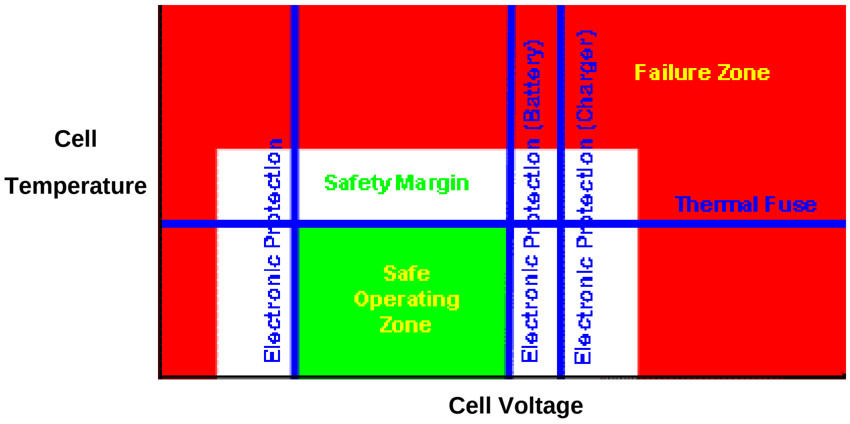
Fast acting over current and overvoltage protection which can isolate the battery are usually provided by electronic means.

Electronic Protection

Over-current protection is normally provided by a current sensing device which detects when the upper current limit of the battery has been reached and interrupts the circuit. Since current is difficult to measure the usual method of current sensing is by measuring the voltage across a low ohmic value, high precision, series, sense resistor in the current path. When the specified current limit has been reached the sensing circuit will trigger a switch which will break the current path. The switch may be a semiconductor device or even a relay. Relays are inexpensive, they can switch very high currents and provide very good isolation in case of a fault but they are very slow to operate. FET switches are normally used to provide fast acting protection but they are limited in their current carrying capability and very costly for high power applications.

Once the fault conditions have been removed, the circuit would normally be reconnected automatically, however there are particular circumstances when the circuit would be latched open. This could be to protect an unsuspecting service engineer investigating why a high voltage battery had tripped out.

Voltage Protection



The above diagram shows a scheme for over and under-voltage, as well as temperature protection. In this case it also shows interaction with the charger. Batteries can be damaged both by over-voltage which can occur during charging and by under-voltage due to excessive discharging. This scheme allows voltage limits to be set for both charging and discharging. Batteries can be particularly vulnerable to overcharging. (See the section on Charging). By providing the charger with inputs from voltage and temperature sensors in the battery, the charger can be cut off when the battery reaches predetermined control limits. The diagram above only shows a single voltage cut off from the charger, however multiple protection circuits can be implemented to provide a comprehensive protection scheme involving the charger as well as the protection built into the battery.

It should be noted that each protection device added into the main current path will increase the effective internal impedance of the battery, as much as doubling it in the case of single cell batteries. This adversely affects the battery's capability of delivering peak power.

Intelligent Batteries

When the charging system involves communications between the battery and the charger it is called an Intelligent Charging System. An example of an Intelligent Battery is provided in the section on Battery Management Systems. An industry standard for specifying the communications link has been defined. This is the SMBus and this is supported by chip sets which have been developed to facilitate this protocol. Although the SMBus is convenient, many manufacturers still prefer to use proprietary solutions.

Monitoring

As well as sending signals to the charger the intelligent battery can turn on warning lights or send signals about the battery condition to the user. Monitoring is an essential component of Battery Management Systems.

Venting

With many cell chemistries the electrochemical process can give rise to the generation of gases, particularly during conditions of over charge. This is called gassing. If the gases are allowed to escape the active mass of chemicals in the cell will be diminished, permanently reducing its capacity and its cycle life. Furthermore the release of chemicals into the atmosphere could be dangerous. Manufacturers have therefore developed sealed cells to prevent this happening. Sealing the cells however gives rise to a different problem. If gassing does occur, pressure within the cell will build up, this will usually be accompanied by a rise in temperature which will make matters worse, until the cell ruptures or explodes. To overcome this second problem sealed cells will normally incorporate some form of vent to release the pressure in a controlled way if it becomes excessive. This is the last line of defence for an abused cell if all the other protection measures fail. Cells are not meant to vent under normal operating conditions.

Circuit Interrupt Device (CID)

For smaller cells an alternative method of dealing with excess pressure is available. This is a small mechanical switch which interrupts the current path through the cell if the internal pressure exceeds a predetermined level. This method is not siutable for high power cells because of the difficulty of incorporating switches which can break the high currents typically causing over-pressure in the cell.

Unfortunately there is no easy way of monitoring the internal pressure of standard cells to facilitate the implementation of simple pressure control mechanisms particularly for high current applications and the product designer is dependent on the efficacy of the safety vent and the use of systems based on temperature monitoring to provide protection from excessive pressure build up within the cells.

See also Pressure Effects.

There is the possibility of explosion if a sealed cell is encased in such a way that it cannot vent. The vents are often tiny and usually go unnoticed. Standard battery holders won't block the vents, but encapsulating the battery in epoxy resin to make a solid power module certainly will.

Multi-cell applications

In multi-cell applications each cell should have its own over-voltage detection device. Several temperature sensors will also be required since the pack may not have a uniform temperature across all the cells. Series connected cell chains would normally require only a single current monitoring and protection device unless provision is made for charging or bypassing individual cells. In such cases each cell will also require its own current monitor. Such complication is unfortunately necessary in high voltage packs containing long series cell strings. This is because individual cells may become overstressed and cause the premature failure of the whole battery. Why this arises, and how to avoid it, is discussed in the section on Cell Balancing.

System Isolation

While the battery can detect and initiate protective actions for events within the battery system, there are some applications which require the battery to respond to external events. This could be an out of tolerance condition such as a high temperature in some other part of the application which requires the power to be shut off. In the case of an automobile accident for instance, an inertia switch should isolate the battery. In these situations the battery needs to incorporate a switch in the main current path which can be triggered by an external signal. This does not necessarily need to be a separate switch since it could be possible to design the battery's over current protection circuit to accept a trigger from an external source.

Capacitive and Inductive Loads

Capacitive and inductive loads may be subject to large current surges as the load charges up. These surges can be sufficient to trip the current protection circuits but may not be of long enough duration to damage the battery. If the application does not allow the current surge to be designed out, then the protection circuit should incorporate a timer or some other device to delay or disable the current cut-off during expected short duration current pulses.

Current Drain

The object of protection is to maximise the life of the battery. Electronic protection circuits themselves draw current from the battery, reducing the effective capacity of the battery to supply the desired load. Low quiescent current is therefore an essential requirement for protection circuits.

Procedures and Discipline

No amount of electronics will protect a cell from bad management practices.

- We know that elevated temperatures are bad for batteries. We should therefore ensure that cells are stored in a cool environment.
- We know that shorting the terminals can be dangerous. We should ensure that handling and packing methods prevent this from happening.
- We know batteries have a finite life. We should make sure the stores works on a FIFO basis.
- Cell manufacturers set operating limits and conditions for their cells. We should ensure that these recommendations are respected during all stages of the procurement, manufacturing and shipping processes.

Protection During Manufacturing

Safe handling procedures for batteries in general are given in the section on User Safety Instructions.

In addition, any electronic circuitry included within the battery pack may be susceptible to damage from electrostatic discharges (ESD) caused by mishandling during the production process. Static electricity may build up on the human body due to contact or friction with insulators and other synthetic materials such as plastics and styrofoam cups, plastic bags and clothing. Its effect is particularly strong in a dry atmosphere. If the charged person then touches an object at a lower potential or ground/earth potential such as circuit boards or components, the charge will be dissipated through that path. This charge is sufficient to damage transistors and integrated circuits. Even if the static sensitive devices are not handled directly they can be damaged by touching the pins or connectors on the printed circuit board.

Standard precautions to avoid electrostatic damage include, the prohibition of casual handling of items on the production line (by visitors or managers), the wearing of grounding straps by anyone touching components or printed circuit boards, conductive flooring, conductive packaging, the labeling of static sensitive components and the avoidance of static prone materials near the production line.

See also Battery Safety

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Battery Management Systems (BMS)

BMS means different things to different people. To some it is simply Battery Monitoring, keeping a check on the key operational parameters during charging and discharging such as voltages and currents and the battery internal and ambient temperature. The monitoring circuits would normally provide inputs to protection devices which would generate alarms or disconnect the battery from the load or charger should any of the parameters become out of limits.

For the power or plant engineer responsible for standby power who's battery is the last line of defence against a power blackout or a telecommunications network outage BMS means Battery Management Systems. Such systems encompass not only the monitoring and protection of the battery but also methods for keeping it ready to deliver full power when called upon and methods for prolonging its life. This includes everything from controlling the charging regime to planned maintenance.

For the automotive engineer the Battery Management System is a component of a much more complex fast acting Energy Management System and must interface with other on board systems such as engine management, climate controls, communications and safety systems.

There are thus many varieties of BMS.

BMS Building Blocks

There are three main objectives common to all Battery Management Systems

- Protect the cells or the battery from damage
- Prolong the life of the battery
- Maintain the battery in a state in which it can fulfil the functional requirements of the application for which it was specified.

To achieve these objectives the BMS may incorporate one or more of the following functions. (Follow the links to see how these functions are implemented.)

- **Cell Protection** Protecting the battery from out of tolerance operating conditions is fundamental to all BMS applications. In practice the BMS must provide full cell protection to cover almost any eventuality. Operating a battery outside of its specified design limits will inevitably lead to failure of the battery. Apart from the inconvenience, the cost of replacing the battery can be prohibitive. This is particularly true for high voltage and high power automotive batteries which must operate in hostile environments and which at the same time are subject to abuse by the user.
- **Charge control** This is an essential feature of BMS. More batteries are damaged by inappropriate charging than by any other cause.
- **Demand Management** While not directly related to the operation of the battery itself, demand management refers to the application in which the battery is used. Its objective is to minimise the current drain on the battery by designing power saving techniques into the applications

circuitry and thus prolong the time between battery charges.

- **SOC Determination** Many applications require a knowledge of the State of Charge (SOC) of the battery or of the individual cells in the battery chain. This may simply be for providing the user with an indication of the capacity left in the battery, or it could be needed in a control circuit to ensure optimum control of the charging process.
- **SOH Determination** The State of Health (SOH) is a measure of a battery's capability to deliver its specified output. This is vital for assessing the readiness of emergency power equipment and is an indicator of whether maintenance actions are needed.
- **Cell Balancing** In multi-cell battery chains small differences between cells due to production tolerances or operating conditions tend to be magnified with each charge / discharge cycle. Weaker cells become overstressed during charging causing them to become even weaker, until they eventually fail causing premature failure of the battery. Cell balancing is a way of compensating for weaker cells by equalising the charge on all the cells in the chain and thus extending battery life.
- **History - (Log Book Function)** Monitoring and storing the battery's history is another possible function of the BMS. This is needed in order to estimate the State of Health of the battery, but also to determine whether it has been subject to abuse. Parameters such as number of cycles, maximum and minimum voltages and temperatures and maximum charging and discharging currents can be recorded for subsequent evaluation. This can be an important tool in assessing warranty claims.
- **Authentication and Identification** The BMS also allows the possibility to record information about the cell such as the manufacturer's type designation and the cell chemistry which can facilitate automatic testing and the batch or serial number and the date of manufacture which enables traceability in case of cell failures.
- **Communications** Most BMS systems incorporate some form of communications between the battery and the charger or test equipment. Some have links to other systems interfacing with the battery for monitoring its condition or its history. Communications interfaces are also needed to allow the user access to the battery for modifying the BMS control parameters or for diagnostics and test.

The following examples illustrate three very different applications of BMS in action.

Intelligent Batteries

The life of rechargeable NiCad and Nickel Metal Hydride batteries such as those used in power tools can be extended by the use of an intelligent charging system which facilitates communications between the battery and the charger. The battery provides information about its specification, its current condition and its usage history which is used by the charger to determine the optimum charging profile or, by the application in which it is used, to control its usage.

The prime objective of the charger/battery combination is to permit the incorporation of a wider range of Protection Circuits which prevent overcharging of, or damage to, the battery and thus extend its life. Charge control can be in either the battery or the charger. The objective of the application/battery combination is to prevent overloads and to conserve the battery. Similar to the charger combination, discharge control can be in either the application or in the battery.

Although some special cells incorporating intelligence have been developed, the intelligence is more likely to be implemented in a battery pack.

The system works as follows:

The Intelligent Battery, or Smart Battery, provides outputs from sensors which give the actual status of voltages, currents and temperatures within the battery as well as the state of charge. It can also provide alarm functions indicating out of tolerance conditions.

The Intelligent Battery also contains a memory chip which is programmed by the manufacturer with information about the battery specification such as:-

- Manufacturing data (Name, date, serial number etc)
- Cell chemistry
- Cell capacity
- Mechanical outline code
- Upper and lower voltage limits
- Maximum current limits
- Temperature limits

Once the battery is placed into use, the memory may also record :-

- How many times the battery has been charged and discharged.
- Elapsed time
- The internal impedance of the battery
- The temperature profile to which it has been subjected
- The operation of any forced cooling circuits
- Any instances when limits have been exceeded.

The system also requires devices which may be in either the battery or the charger or both which can interrupt or modify the charging according to a set of rules. Similarly, battery discharge can be controlled by the battery or demand management circuits in the application.

The Intelligent Battery also needs an Intelligent Charger it can talk to and a language they can speak.

The charger is programmed to respond to inputs from the battery, to optimise the charging profile, charging at the maximum rate until a preset temperature is reached, then slowing down or stopping the charge and or switching on a cooling fan so as not to exceed the temperature limit and thus avoid permanent damage to the battery. If a deterioration in the battery internal impedance indicates that reconditioning is necessary the charger can also be programmed to reform the battery by subjecting it to several deep charge, discharge cycles. Because the battery contains information about its specification which can be read by the charger, it is possible to build Universal Chargers which can automatically adapt the charging profile to a range of battery chemistries and capacities, so long as they comply with an agreed message protocol.

A separate communications channel is needed to facilitate interactions between the battery and the charger. One example used for simple applications is the System Management Bus (SMBus) which forms part of the Smart Battery System which is used mainly in low power applications. Batteries which comply with the SBS standard are called Smart Batteries. Intelligent batteries are however not limited to the SMS scheme and many manufacturers have implemented their own proprietary schemes which may be simpler or more complex, depending on the requirements of the application.

A 50% increase in battery life has been claimed by using such techniques.

Automatic Control System

This is an example of an Automatic Control System in which the battery provides information about its actual condition to the charger which compares the actual condition with the desired condition and generates an error signal which is used to initiate control actions to bring the actual condition into line with the desired condition. The control signals form part of a Feedback Loop which provides automatic compensation to keep the battery within its desired operating parameters. It does not require any user intervention. Some form of automatic control system is an essential part of all BMS

Battery Monitoring

As well as talking to the charger, the Intelligent Battery can also talk to the user or to other systems of which the battery may be a part. The signals it provides can be used to turn on warning lights or to inform the user about the condition of the battery and how much charge it has left.

Monitoring the battery condition is an essential part of all Battery Management Systems. In the first of the following two examples, the control actions are manual, - the power plant maintenance engineer fixes any deficiencies. In the second example the battery is part of an Automatic Control System made up from several interlinked feedback loops controlling the battery itself and its role as part of the overall vehicle energy management system.

Power Plant BMS

The battery management requirements are quite different for standby and emergency power installations. Batteries may be inactive for long periods topped up by a trickle charge from time to time, or as in telecommunications installations they may be kept on float charge to keep them fully charged at all times. By their nature, such installations must be available for use at all times. An essential responsibility of managing such installations is to know the status of the battery and whether it can be relied upon to support its load during an outage. For this it is vital to know the SOH and the SOC of the battery. In the case of lead acid batteries the SOC of individual cells can be determined by using a hydrometer to measure the specific gravity of the electrolyte in the cells. Traditionally, the only way of determining the SOH was by discharge testing, that is, by completely discharging the battery and measuring its output. Such testing is very inconvenient. For a large installation it could take eight hours to discharge the battery and another three days to recharge it. During this time the installation would be without emergency power unless a back up battery was provided.

The modern way to measure the SOH of a battery is by impedance testing or by conductance testing . It has been found that a cell's impedance has an inverse correlation with the SOC and the conductance being the reciprocal of the impedance has a direct correlation with the SOH of the cell. Both of these tests can be carried out without discharging the battery, but better still the monitoring device can remain in place providing a permanent on line measurement. This allows the plant engineer to have an up to date assessment of the battery condition so that any deterioration in cell performance can be detected and appropriate maintenance actions can be planned.

Automotive BMS

Automotive battery management is much more demanding than the previous two examples. It has to interface with a number of other on board systems, it has to work in real time in rapidly changing charging and discharging conditions
as the vehicle accelerates and brakes, and it has to work in a harsh and uncontrolled environment. This example describes a complex system as an illustration of what is possible, however not all applications will require all the functions shown here.

The functions of a BMS suitable for a hybrid electric vehicle are as follows:

- Monitoring the conditions of individual cells which make up the battery
- Maintaining all the cells within their operating limits
- Protecting the cells from out of tolerance conditions
- Providing a "Fail Safe" mechanism in case of uncontrolled conditions or abuse
- Isolating the battery in cases of emergency
- Compensating for any imbalances in cell parameters within the battery chain
- Setting the battery operating point to allow regenerative braking charges to be absorbed without overcharging the battery.
- Providing information on the State of Charge (SOC) of the battery. This function is often referred to as the "Fuel Gauge" or "Gas Gauge "
- Providing information on the State of Health (SOH) of the battery. This measurement gives an indication of the condition of a used battery

relative to a new battery.

- Providing information for driver displays and alarms
- Predicting the range possible with the remaining charge in the battery (Only EVs require this)
- Accepting and implementing control instructions from related vehicle systems
- Providing the optimum charging algorithm for charging the cells
- Providing pre-charging to allow load impedance testing before switch on and two stage charging to limit inrush currents
- Providing means of access for charging individual cells
- Responding to changes in the vehicle operating mode
- Recording battery usage and abuse. (The frequency, magnitude and duration of out of tolerance conditions) Known as the Log Book function
- Emergency "Limp Home Mode" in case of cell failure.

In practical systems the BMS can thus incorporate more vehicle functions than simply managing the battery. It can determine the vehicle's desired operating mode, whether it is accelerating, braking, idling or stopped, and implement the associated electrical power management actions.

Cell Protection

One of the prime functions of the Battery Management System is to provide the necessary monitoring and control to protect the cells from out of tolerance ambient or operating conditions. This is of particular importance in automotive applications because of the harsh working environment. As well as individual cell protection the automotive system must be designed to respond to external fault conditions by isolating the battery as well as addressing the cause of the fault. For example cooling fans can be turned on if the battery overheats. If the overheating becomes excessive then the battery can be disconnected.

Protection methods are discussed in detail in the section on Protection.

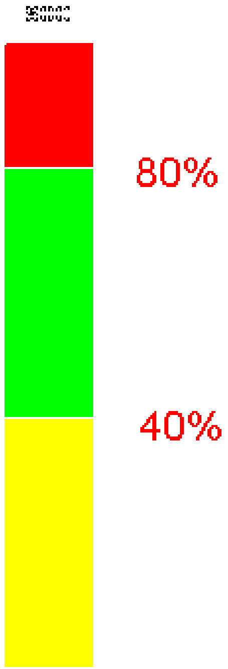
Battery State of Charge (SOC)

Determining the State of Charge (SOC) of the battery is the second major function of the BMS. The SOC is needed not just for providing the Fuel Gauge indication. The BMS monitors and calculates the SOC of each individual cell in the battery to check for uniform charge in all of the cells in order to verify that individual cells do not become overstressed.

The SOC indication is also used to determine the end of the charging and discharging cycles. Over-charging and over-discharging are two of the prime causes of battery failure and the BMS must maintain the cells within the desired DOD operating limits.

Hybrid vehicle batteries require both high power charge capabilities for regenerative braking and high power discharge capabilities for launch assist or boost. For this reason, their batteries must be maintained at a SOC that can discharge the required power but still have enough headroom to accept the necessary regenerative power without risking overcharging the cells. To fully charge the HEV battery for cell balancing (See below) would diminish charge acceptance capability for regenerative braking and hence braking efficiency. The lower limit is set to optimise fuel economy and also to prevent over discharge which could shorten the life of the battery. Accurate SOC information is therefore needed for HEVs to keep the battery operating within the required, safe limits.

HEV Battery Operating Range

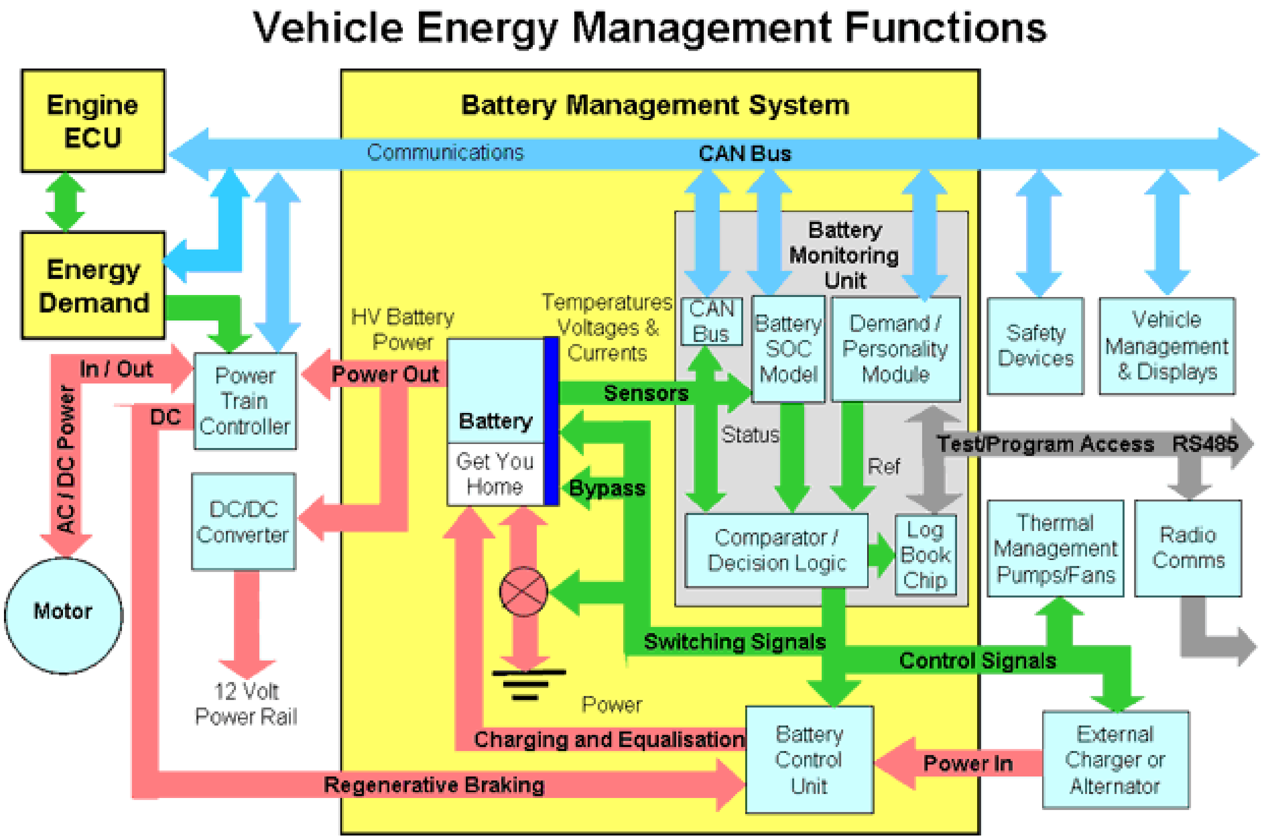


Methods of determining the SOC are described in the section on State of Charge.

The Battery Management System

The diagram below is a conceptual representation of the primary BMS functions. It
shows the three main BMS building blocks, the Battery Monitoring Unit (BMU), the Battery Control Unit (BCU) and the CAN bus vehicle communications network and how they interface with the rest of the vehicle energy management systems. Other configurations are possible with distributed BMS embedded in the battery cell to cell interconnections.

In practice the BMS may also be coupled to other vehicle systems which communicate with the BMS via the CAN bus (see below) such as the Thermal Management System or to anti theft devices which disable the battery. There may also be requirements for system monitoring and programming, and data logging using an RS232 serial bus.



Battery Monitoring Unit

The Battery Monitoring Unit is a microprocessor based unit incorporating three functions or sub-modules. These sub-modules are not necessarily separate physical units but are shown separately here for clarity.

Battery Model

The Battery Model characterises in a software algorithm, the behaviour of the battery in response to various external and internal conditions. The model can then use these inputs to estimate the status of the battery at any instant in time.

An essential function of the battery model is to calculate the SOC of the battery for the functions noted above.

The SOC is determined essentially by integrating the current flow over time, modified to take account of the many factors which affect the performance of the cells, then subtracting the result from the known capacity of the fully charged battery. This is described in detail in the section on SOC.

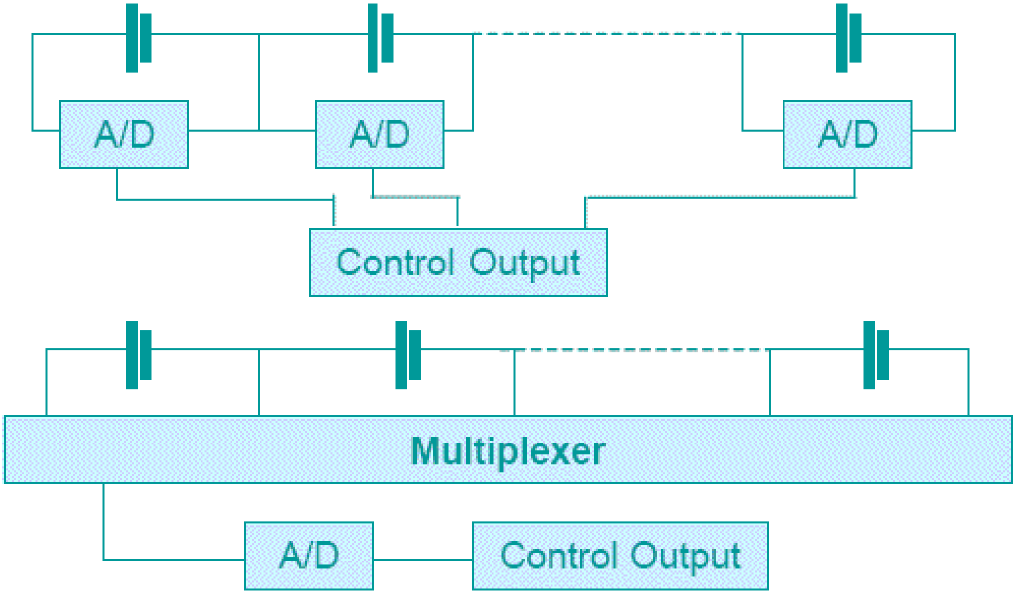
The battery model can be used to log past history for maintenance purposes or to predict how many miles the vehicle may run before the battery needs recharging. The remaining range, based on recent driving or usage patterns, is calculated from the current SOC and the energy consumed and the miles covered since the previous charge (or alternatively from a previous long term average). The distance travelled is derived from data provided by other sensors on the CAN bus (see below).
The accuracy of the range calculation is more important for EVs whose only source of power is the battery. HEVs and bicycles have an alternative "Get you home" source of power should the battery become completely discharged.

The problem of losing all power when a single cell fails can be mitigated at the cost of adding four more expensive contactors which effectively split the battery into two separate units. If a cell should fail, the contactors can isolate and bypass the half of the battery containing the failed cell allowing the vehicle to limp home at half power using the other (good) half of the battery.

Outputs from the model are sent to the vehicle displays also using the CAN bus.

Multiplexing

To reduce costs, instead of monitoring each cell in parallel, the Battery Monitoring Unit incorporates a multiplexing architecture which switches the voltage from each cell (input pairs) in turn to a single analogue or digital output line (see below). Cost savings can be realized by reducing the number of analogue control and/or digital sampling circuits and hence the component count to a minimum. The drawbacks are that only one cell voltage can be monitored at a time. A high speed switching mechanism is required to switch the output line to each cell so that all cells can be monitored sequentially.



Multiplexing to reduce component count

The BMU also provides the inputs for estimating the SOH of the battery, however since the SOH changes only gradually over the lifetime of the battery, less frequent samples are needed. Depending on the method used to determine the SOH, sampling intervals may be as low as once per day. Impedance measurements for example could even be taken only in periods when the vehicle is not in use. Cycle counting of course can only occur when the vehicle is operational.

Demand or Personality Module

The Demand Module is similar in some respects to the Battery Model in that it contains a reference model with all the tolerances and limits relevant to the various parameters monitored by the Battery Model. The Demand Module also takes instructions from the communications bus such as commands from the BMS to accept a regenerative braking charge or from other vehicle sensors such as safety devices or directly from the vehicle operator. This unit is also used to set and to monitor the vehicle operating mode parameters.

This module is sometimes called the Personality Module since includes provision for programming into the system, all the custom requirements which may be specific to the customer's application. For example, the cell maker will recommend a temperature limit at which for safety reasons the battery must be automatically disconnected. However the car manufacturer may set two lower limits, one at which forced cooling may be switched on and another which lights up a warning light on the driver's instrument panel.

For HEV applications, the Personality Module interfaces with the engine Electronic Control Unit (ECU) via the CAN bus. Provision is made in this module for setting the desired system SOC operating range and the parameters for controlling the power sharing between the electric drive and the internal combustion engine .

The Demand Module also contains a memory block for holding all the reference data and for accumulating the historical data used for monitoring the battery SOH. Data to display the SOH or switch on warning lights can be provided to the vehicle instrumentation module via the CAN bus.

The outputs from the Demand Module provide the reference points for setting the operating conditions of the battery or triggering the action of protection circuits.

Test access to the BMS for monitoring or setting system parameters and for downloading the battery history is provided through a standard RS 232 or RS485 serial bus.

Decision Logic Module

The Decision Logic module compares the status of the measured or calculated battery parameters from the Battery Model with the desired or reference result from the Demand Module. Logic circuits then provide error messages to initiate cell protection actions or to be used in the various BMS feedback loops which drive the system to its desired operating point or isolate the battery in the case of unsafe conditions. These error messages provide the input signals for the Battery Control Unit.

System Communications

The BMS needs a communications channel for passing signals between its various internal functional circuit blocks. It must also interface with several external vehicle systems for monitoring or controlling remote sensors, actuators, displays, safety interlocks and other functions.

Automotive BMS therefore uses the CAN bus which was designed for this purpose as its main communications channel.

Battery Control Unit

The Battery Control Unit contains all the BMS power electronics circuitry. It takes control signals from the Battery Monitoring Unit to control the battery charging process and to switch the power connections to individual cells.

Some of the possible functions of this unit are:

- Controlling the voltage and current profile of the charger output during the charging process.

- Providing top up charge to individual cells to equalise the charge on all cells in the battery chain.
- Isolating the battery during fault or alarm conditions
- Switching the regenerative braking charge into the battery as required
- Dumping excessive regenerative braking charges when the battery is fully charged
- Responding to changes in the vehicle operating mode

To provide these functions, each cell in the battery may require expensive high current switches capable of switching 200 Amps or more to provide the necessary interconnections.

- **Binary Control and Progressive Control**

  In its simplest form, the BMS privides a "binary" ON/OFF resonse to a fault or an out of tolerance condition such as an overload, merely isolating the battery completely by opening the main contactors. Progressive or variable control can however be provided in the case of an overload by utilising the CAN Bus to call for a reduced the demand on the battery.

Cell Balancing

This is another essential function of the automotive BMS. As noted above it is required to compensate for weaknesses in individual cells which could eventually cause the failure of the complete battery. The reasons for cell balancing and how this is implemented are explained on the Cell Balancing page.

Limp Home Mode

Although batteries are designed to be trouble free for 3 or more years, there is always the possibility that the battery could be disabled by the failure of a single cell. If a cell goes open circuit, the battery is essentially dead. However the BMS is designed to monitor the status of every cell and so the location of the faulty cell will automatically be identified. It is not difficult to split the battery into two sections in series, each of which can be independently bypassed by disconnecting the section of the battery containing the faulty cell and switching a conducting link in its place. This will allow the vehicle to get to home or to the nearest refuge on half power using the good section of the battery. As well as the links the system will need two more expensive high power contactors to implement this function, but this investment may be well justified when the alternative could be a costly and dangerous breakdown on the motorway.

System Enhancements

Automotive BMSs may also be required to provide various functions which are not necessarily essential to managing the battery. These may include remote monitoring of the battery from the fleet headquarters and this may also include the GPS location of the vehicle. The driver could thus be warned if the vehicle was getting low on charge or if he was straying too far from a charging station.

Fortunately not all BMS applications are as complex as this one.

Practical BMS Implementation

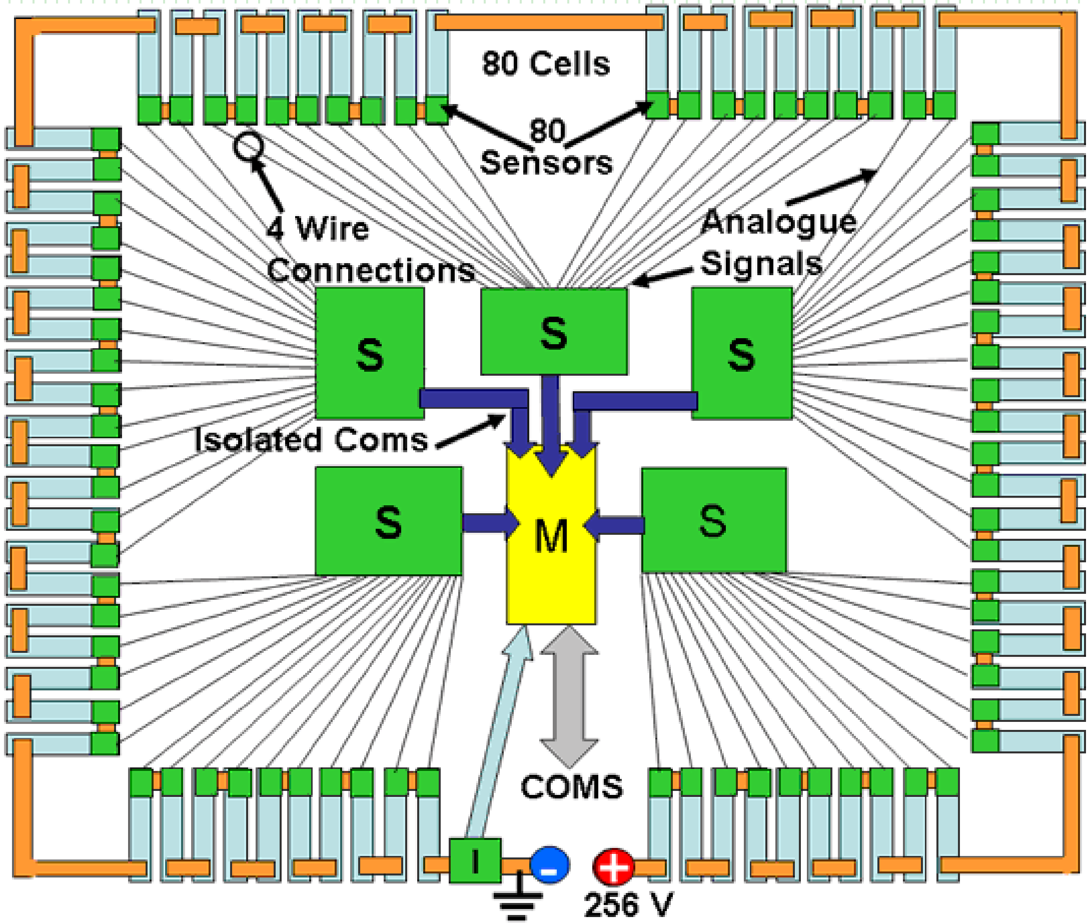
There are many ways of implementing the battery management system and two different examples for a 256 Volt battery made up from 80 Lithium Iron Phosphate cells are shown below.

Master and Slaves

The master and slaves, star topolgy, organises the cells into blocks or modules with one slave managing each module. In the example shown, 16 X 3.2 volt cells are arranged in modules each with an output voltage of 51.2 Volts but other module sizes and voltages are possible.

- **The Slaves -** Each cell has a temperature sensor as well as connections to measure the voltage, all of which are connected to the slave which monitors the condition of the cell and implements the cell balancing.
- **The Master -** Multiple slaves can be connected to the master which monitors the current and integrates it over time to calculate the net Coulomb flow and this is modified using voltage and temperature data from the slaves to calculate the battery SOC. The master controls the main battery isolation contactor(s) initiating battery protection in response to data from the main current sensor or voltage and temperature data from the slaves.The master also provides the system communications.

BMS Master and Slaves (Star Topology)



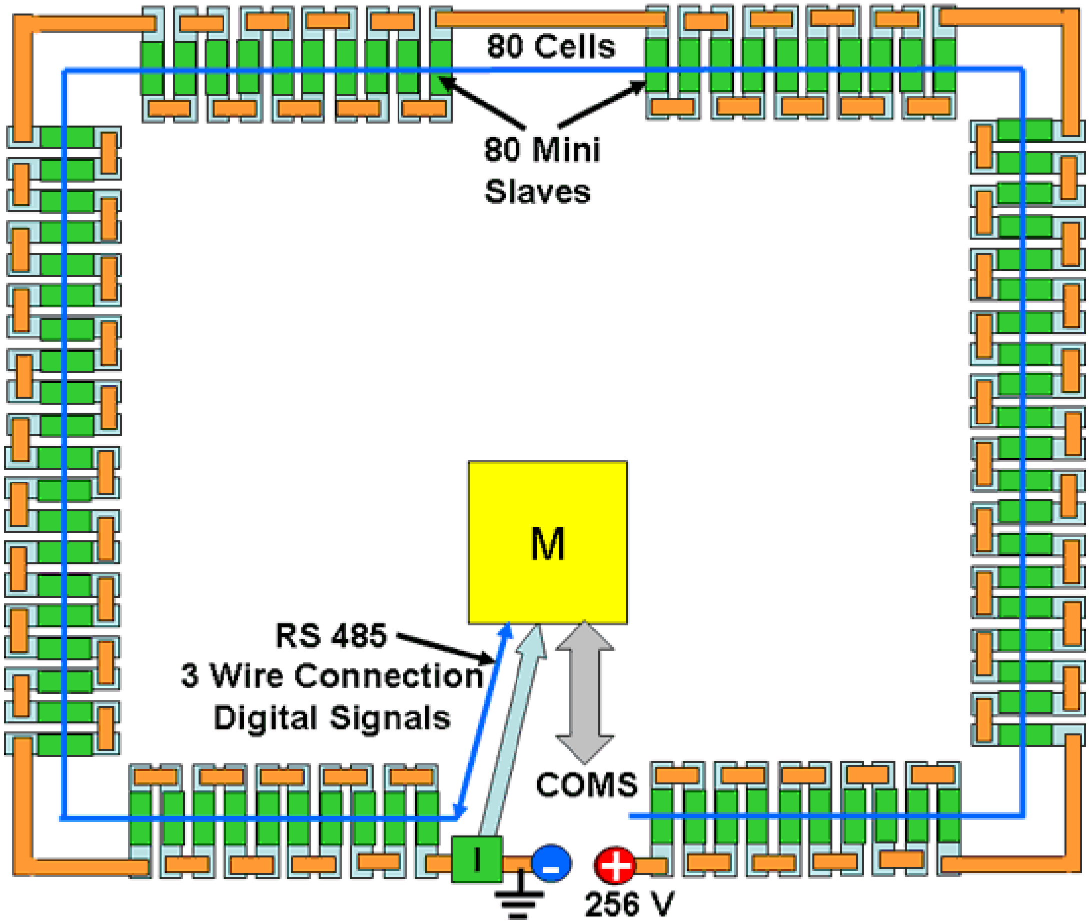
This configuration has the advantages that it does not need printed circuit boards connected to individual cells and high voltage batteries can be accommodated by adding more modules and since the main battery current does not pass through slaves, it can also be used for high current batteries. Signal processing is shared between the master and the slaves simplifying the management of the information processing load.

Disadvantages are that the communications between the sensors and the slaves are in analogue form, and thus susceptible to noise, and the very large number of sensor wires, four per cell, which are required. Opto-isolated connections between the slaves and the master are also required since the votages on the slaves would otherwise be progressively higher, up to the full battery voltage, as connections are taken from further up the cell chain.

BMS Daisy Chain

The daisy chain, ring topology, uses a small simple slave printed circuit board connected to each cell to accommodate the voltage and temperature sensors with an A to D converter, as well as a current bypass switch to enable cell balancing by charge shunting and an communications transceiver with built in capacitive isolation for receiving and transmitting data in digital form. The slave takes its power from the cell it is monitoring and a single RS 485 three wire data bus connects the nodes from all the slaves to the master which polls each node in turn and requests an update of its cell conditions. The slave does not carry out any signal processing, apart from the A to D conversion, as this is all carried out by the master along with all the monitoring, protection and communications functions as in the example above.

BMS Daisy Chain (Ring Topology)



The main advantages of this topology are its simpler design and construction and its potential for higher reliability in an automotive environment.

The disadvantages are the large number of mini-slave printed circuit boards which are needed and the difficulty of mounting them on some cell types. In addition the master has a higher processing load.

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Cell Balancing

In multicell batteries, because of the larger number of cells used, we can expect that they will be subject to a higher failure rate than single cell batteries. The more cells used, the greater the opportunities to fail and the worse the reliability.

Batteries such as those used for EV and HEV applications are made up from long strings of cells in series in order to achieve higher operating voltages of 200 to 300 Volts or more are particularly vulnerable. The problems can be compounded if parallel packs of cells are required to achieve the desired capacity or power levels. With a battery made up from n cells, the failure rate for the battery will be n times the failure rate of the individual cells.

All cells are not created equal

The potential failure rate is even worse than this however due to the possibility of interactions between the cells. Because of production tolerances, uneven temperature distribution and differences in the ageing characteristics of particular cells it is possible that individual cells in a series chain could become overstressed leading to premature failure of the cell. During the charging cycle, if there is a degraded cell in the chain with a diminished capacity, there is a danger that once it has reached its full charge it will be subject to overcharging until the rest of the cells in the chain reach their full charge. The result is temperature and pressure build up and possible damage to the cell. During discharging, it is even possible for the voltage on the weaker cells to be reversed as they become fully discharged before the rest of the cells resulting in failure of the cell.

Balancing is less of a problem with parallel chains which tend to be self balancing.

See Interactions Between Cells for more details.

The problems caused by these cell to cell differences are exaggerated when the cells are subject to the rapid charge and discharge cycles (microcycles) found in HEV applications.

While Lithium batteries are more tolerant of micro cycles they are less tolerant of the problems caused by cell to cell differences.

Because Lead acid and NiMH cells can withstand a level of over-voltage without sustaining permanent damage, a degree of cell balancing or charge equalisation can occur naturally with these technologies simply by prolonging the charging time since the fully charged cells will release energy by gassing until the weaker cells reach their full charge. This is not possible with Lithium cells which can not tolerate over-voltages.

Although the problem is reduced with Lead acid NiMH batteries and some other cell chemistries, it is not completely eliminated and solutions must be found for most multicell applications.

No matter what battery management techniques are used, the failure rate or cycle life of a multicell battery will always be worse than the quoted failure rate or cycle life of the single cells used to make up the battery.

Once a cell has failed, the entire battery must be replaced and the consequences are extremely costly. Replacing individual failed cells does not solve the problem since the characteristics of a fresh cell would be quite different from the aged cells in the chain and failure would soon occur once more. Some degree of refurbishment is possible by cannibalising batteries of similar age and usage but it can never achieve the level of cell matching and reliability possible with new cells.

Equalisation is intended to prevent large long term unbalance rather than small short term deviations.

Cell selection

The first approach to solving this problem should be to avoid it if possible through cell selection. Batteries should be constructed from matched cells, preferably from the same manufacturing batch. Testing can be employed to classify and select cells into groups with tighter tolerance spreads to minimise variability within groups.

Pack construction

Another important avoidance action is to ensure at all times an even temperature distribution across all cells in the battery. Note that in an EV or HEV passenger car application, the ambient temperature in the engine compartment, the passenger compartment and the boot or trunk can be significantly different and dispersing the cells throughout the vehicle to spread the mechanical load can give rise to unbalanced thermal operating conditions. On the other hand, if the cells are concentrated in one large block, the outer cells in contact with ambient air may run cooler than the inner cells which are surrounded by warmer cells unless steps are taken to provide an air (or other coolant) flow to remove heat from the hotter cells. See also Thermal Management

Cell equalisation

To provide a dynamic solution to this problem which takes into account the ageing and operating conditions of the cells, the BMS may incorporate a Cell Balancing scheme to prevent individual cells from becoming overstressed. These systems monitor the State of Charge (SOC) of each cell, or for less critical, low cost applications, simply the voltage across, each cell in the chain. Switching circuits then control the charge applied to each individual cell in the chain during the charging process to equalise the charge on all the cells in the pack. In automotive applications the system must be designed to cope with the repetitive high energy charging pulses such as those from regenerative braking as well as the normal trickle charging process.

Several Cell Balancing schemes have been proposed and there are trade-offs between the charging times, efficiency losses and the cost of components.

Active balancing

Active cell balancing methods remove charge from one or more high cells and deliver the charge to one or more low cells. Since it is impractical to provide independent charging for all the individual cells simultaneously, the balancing charge must be applied sequentially. Taking into account the charging times for each cell, the equalisation process is also very time consuming with charging times measured in hours. Some active cell balancing schemes are designed to halt the charging of the fully charged cells and continue charging the weaker cells till they reach full charge thus maximising the battery's charge capacity.

- **Charge Shuttle (Flying Capacitor) Charge Distribution**

  With this method a capacitor is switched sequentially across each cell in the series chain. The capacitor averages the charge level on the cells by picking up charge from the cells with higher than average voltage and dumping the charge into cells with lower than average voltage. Alternatively the process can be speeded up by programming the capacitor to repeatedly transfer charge from the highest voltage cell to the lowest voltage cell. Efficiency is reduced as the cell voltage differences are reduced. The method is fairly complex with expensive electronics.
- **Inductive Shuttle Charge Distribution**

  This method uses a transformer with its primary winding connected across the battery and a secondary winding which can be switched across individual cells. It is used to take pulses of energy as required from the full battery, rather than small charge differences from a single cell, to top up the remaining cells. It averages the charge level as with the Flying Capacitor but avoids the problem of small voltage differences in cell voltage and is consequently much faster.

Passive balancing

Dissipative techniques find the cells with the highest charge in the pack, indicated by the higher cell voltage, and remove excess energy through a bypass resistor until the voltage or charge matches the voltage on the weaker cells. Some passive balancing schemes stop charging altogether when the first cell is fully charged, then discharge the fully charged cells into a load until they reach the same charge level as the weaker cells. Other schemes are designed continue charging till all the cells are fully charged but to limit the voltage which can be applied to individual cells and to bypass the cells when this voltage has been reached.

This method levels downwards and because it uses low bypass currents, equalisation times are very long. Pack performance determined by the weakest cell and is lossy due to wasted energy in the bypass resistors which could drain the battery if operated continuously. It is however the lowest cost option.

Charge Shunting

The voltage on all cells levelled upwards to the rated voltage of a good cell. Once the rated voltage on a cell has been reached, the full current bypasses fully charged cells until the weaker cells reach full voltage. This is fast and allows maximum energy storage however it needs expensive high current switches and high power dissipating resistors.

Charge limiting

A crude way of protecting the battery from the effects of cell imbalances is to simply switch off the charger when the first cell reaches the voltage which represents its fully charged state (4.2 Volts for most Lithium cells) and to disconnect the battery when the lowest cell voltage reaches its cut off point of 2 Volts during discharging. This will unfortunately terminate the charging before all of the cells have reached their full charge or cut off the power prematurely during discharge leaving unused capacity in the good cells. It thus reduces the effective capacity of the battery. Without the benefits of cell balancing, cycle life could also be reduced, however for well matched cells operating in an even temperature environment, the effect of these compromises could be acceptable.

All of these balancing techniques depend on being able to determine the state of charge of the individual cells in the chain. Several methods for determining the state of charge are described on the SOC page.

The simplest of these methods uses the cell voltage as an indication of the state of charge. The main advantage of this method is that it prevents overcharging of individual cells, however it can be prone to error. A cell may reach its cut off voltage before the others in the chain, not because it is fully charged but because its internal impedance is higher than the other cells. In this case the cell will actually have a lower charge than the other cells. It will thus be subject to greater stress during discharge and repeated cycling will eventually provoke failure of the cell.

More precise methods use Coulomb counting and take account of the temperature and age of the cell as well as the cell voltage.

Redox Shuttle (Chemical Cell Balancing)

In Lead acid batteries, overcharging causes gassing which coincidentally balances the cells. The Redox Shuttle is an attempt to provide chemical overcharge protection in Lithium cells using an equivalent method thus avoiding the need for electronic cell balancing. A chemical additive which undergoes reversible chemical action absorbing excess charge above a preset voltage is added to the electrolyte . The chemical reaction is reversed as voltage falls below the preset level.

For batteries with less than 10 cells, where low initial cost is the main objective, or where the cost of replacing a failed battery is not considered prohibitive, cell balancing is sometimes dispensed with altogether and long cycle life is achieved by restricting the permitted DOD. This avoids the cost and complexity of the cell balancing electronics but the trade off is inefficient use of cell capacity.

Whether or not the battery employs cell balancing, it should always incorporate fail safe cell protection circuits.

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Capacitors and SuperCapacitors

Characteristics

Capacitors store energy in an electrostatic field rather than as a chemical state as in batteries.

No chemical actions involved which means very long cycle life is possible.

No limit on the cell voltage imposed by the "cell chemistry" as with galvanic cells.

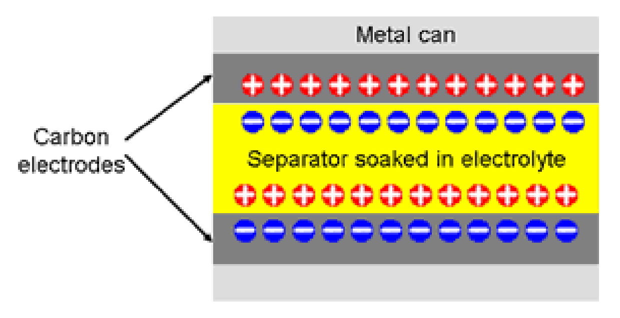
The terminal voltage directly proportional to the State of Charge (SOC) which limits range of applicability somewhat.

Low power capacitors

Capacitors are probably the most common form of non-chemical energy storage and are widely used in low power applications.

Typical specification: 20 μF to 2 Farads 5.5 to 6.3 Volts

Supercapacitors, **Ultracapacitors** or **EDLC (Electric Double Layer Capacitors)** as they are also called, look very much like batteries. They have double layer construction consisting of two carbon electrodes immersed in an organic electrolyte. See below



Double Layer Capacitor

During charging, the electrically charged ions in the electrolyte migrate towards the electrodes of opposite polariity due to the electric field between the charged electrodes created by the applied voltage. Thus two separate charged layers are produced. Although similar to a battery, the double layer capacitor depends on electrostatic action. Since no chemical action is involved the effect is easily reversible and the typical cycle life is hundreds of thousands of cycles.

They have a low energy density of less than 15 Wh/Kg but a very high power density of 4,000 W/Kg and capacitance values of thousands of Farads are possible. Although the power density is very high the cell voltage is limited to about 2.3 Volts to avoid electrolysis of the electrolyte with the consequent emission of gas.

Voltage equalisation to spread the available charge evenly between the capacitors in a series chain may also be needed for many applications.

Typical specification of capacitor banks for automotive applications: 10 to 200 Farads 100 Volts

Advantages

Cell voltage determined by the circuit application, not limited by the cell chemistry.

Very high cell voltages possible (but there is a trade-off with capacity)

High power available.

High power density.

Simple charging methods. No special charging or voltage detection circuits required.

Very fast charge and discharge. Can be charged and discharged in seconds.

Can not be overcharged.

Long cycle life of more than 500,000 cycles at 100% DOD.

No chemical actions.

10 to12 year life

Low impedance

Shortcomings

Linear discharge voltage characteristic prevents use of all the available energy in some applications.

Power only available for a very short duration.

Low capacity.

Low energy density. (6Wh/Kg)

Cell balancing required for series chains.

High self discharge rate. Much higher than batteries.

Applications

Applications requiring a short duration power boost.

Low power

Capacitors are extensively used as power back-up for memory functions in a wide range of consumer products such as mobile phones, laptops and radio tuners.

Used in pulsed applications to share the load and for providing peak power assistance to reduce the duty cycle on the battery to prolong battery life in products or devices using mechanical actuators such as digital cameras. See also Load Sharing.

Also used for energy storage for solar panels, and motor starters.

High power

The shortcomings above render supercapacitors unsuitable as primary power source for EV and HEV applications however their advantages make them ideal for temporary energy storage for capturing and storing the energy from regenerative braking and for providing a booster charge in response to sudden power demands.

Since the capacitor is normally connected in parallel with the battery in these applications, it can only be charged up to the battery upper voltage level and it can only be discharged down to the battery lower discharge level, leaving considerable unusable charge in the capacitor, thus limiting its effective or useful energy storage capacity.

Using supercapacitors in EVs and HEVs to facilitate regenerative braking can add 15% to 25% to the range of the vehicle.

At the same time, supercapacitors can provide an effective short duration peak power boost allowing the prime battery to be downsized.

It should be noted however that while supercapacitors can be used to to provide the increased range and short term power, it is at the cost of considerable added weight and bulk of the system, and this should be weighed against the advantages of using higher capacity batteries.

Supercapacitors are also used to provide fast acting short term power back up for UPS applications. By combining a capacitor with a battery-based uninterruptible power supply system, the life of the batteries can be extended. The batteries provide power only during the longer interruptions, reducing the peak loads on the battery and permitting the use of smaller batteries.

Carbon Nanotube Enhanced Supercapacitors

Recent developments at MIT have shown that the performance of supercapacitors can be significantly improved by using nanomaterials. The energy storage capability of a capacitor is directly proportional to its capacitance which in turn is proportional to the area of the plates or electrodes. Likewise the current carrying capability is directly proportional to the area of the electrodes. By using vertically aligned, single-wall carbon nanotubes which are only several atomic diameters in width instead of the porous, amorphous carbon normally employed, the effective area of the electrodes can be dramatically increased. While the achievable energy density of 60Wh/Kg still can not match the level obtainable in Lithium Ion batteries (120Wh/kg), the power densities achieved of 100kW/kg are three orders of magnitude better than batteries.

Commercial products are not yet available but should be soon.

More information on Alternative Energy Storage Methods page.

See also History (Electrolytic Capacitors)

Costs

Cell Chemistry Comparison Chart

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Demand Management

In any system incorporating batteries one of the major design goals is to maximise the time between charges. Battery design engineers try to achieve this goal by providing cells with the maximum possible capacity. The product design engineer however can play a major role in helping the battery charge to last longer by using power management schemes in their designs which reduce the current drain on the battery. Since a given charge can be made to last longer or to do more useful work, a consequential benefit is that for the same cycle life, the actual battery lifetime will also be extended.

In general power management schemes reduce the overall power consumption by supplying power only to parts of the circuit which have an immediate demand for it and slowing down, or switching off the power to, circuits which may be temporarily idle. This may be done progressively as in laptop computers or according to a preprogrammed sampling scheme which allows power on demand as in mobile phones.

Progressive Circuit Shut Down

This technique is used extensively in laptop computer designs. By sensing the keyboard activity the computer knows when the machine is idle. After set intervals of inactivity certain functions are switched off. A measure of user control over the length of the intervals is usually provided to enable the user to match the shut down scheme to his work pattern. The shorter the intervals the more power will be saved. The functions are usually restored immediately when the computer senses that the mouse or keyboard have been used again.

Shut Down Sequence

- First the monitor or screen is switched off.
- If there is still no activity the hard disks may be switched off.
- Standby Mode is the next stage in the shut down. - This places the entire system in a low-power state by slowing down the clock speed and hence all the circuit functions. All the open applications remain in place and ready to restart on demand. This gives the benefit of getting right back to work when required without waiting for the computer to restart.
- Hibernation is the last shut down stage which occurs when there has been no activity for a prolonged period. In this state all the contents of memory are first stored in a special file on the hard disk and then the central processing unit or the entire computer is switched off. When the computer is powered up again it must first reboot but everything will be restored exactly as it was left including programs and documents which may not have saved or closed.

There are other things the computer user can do to preserve battery life. The most obvious one is to disconnect the battery when mains power is available. It is a pity laptop manufacturers don't provide a switch for this purpose. It usually requires removing the battery.

LCD screens are notoriously power hungry devices. Their appetite can however be reduced by turning down the brightness control.

PDAs, unlike laptop computers, have no hard drives.They can only store data in volatile memory and so can never be completely switched off. The power management circuitry must still supply keep-alive voltage to the sleeping processor and memory when the PDA is not in use, and it must do it at extremely low quiescent current.

Power On Demand

Mobile phones need to be switched on at all times to be able to receive calls, but they don't need to be transmitting unless there is some information to transmit. The receiver is a low power circuit processing low received signal levels, but the transmitter has to send out high power signals strong enough to reach the base station. The audio amplifier and display circuits also consume high power but are only needed during actual call. The following techniques are used to conserve power:-

- The transmitter has to keep the base station informed about the location of the handset and to check if there are any incoming calls so it must send out regular signals to the base station to keep it updated .The transmitter is therefore only switched on for about half a millisecond every second (the exact period depends on the system design) to tell the base station where it is.
- The audio, display and other feature circuits are switched to a low power sleep mode between calls. In response to the transmitter paging the base station, if there is an incoming call, a wake up circuit will turn on all of these functions again.
- During a call, when it needs to transmit speech, it only uses power if there is information to be transmitted.
- Automatic gain control ensures that, when it is transmitting, the communications link is maintained with just sufficient transmitter power consistent with acceptable signal quality.

Intelligent Energy Manager (IEM)

New developments in microprocessor and software technology recently announced by ARM enable dynamic tuning of the processor's operating voltage and frequency to match the processing workload. Reductions in the processor's energy consumption by up to 25% are claimed for applications using this technique, extending the battery life for portable systems.

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Why Batteries Fail

For the applications engineer designing reliable products dependent on batteries for power an understanding of the potential failure modes of the cells employed is essential. This is to enable him to ensure that potential faults have been designed out of the cells themselves and that unsuitable or uncontrolled operating conditions during manufacture or use of the cells can be prevented or avoided. Batteries with different cell chemistries or constructions may fail in different ways. This report outlines some of the most common cell failures and suggests preventative measures which need to be considered when specifying cells for a new battery application.

Why Cells Fail

Cell design faults

The logical place to start the analysis is in the design of the cell itself. Unfortunately it is the area where the applications design engineer has least knowledge and which he is least able to influence. Cell design faults such as weak mechanical design, inadequate pressure seals and vents, the specification of poor quality materials and improperly specified tolerances can be responsible for many potential failures. Unless he is qualified in physical chemistry, and has experience in components design and access to detailed cell design data and specialist equipment such as mass spectrometers and electron microscopes, there's not much the applications engineer can do to assure himself of the quality of the cell design just from the specifications. What can be done however is accelerated life testing on sample cells to verify that they meet the desired reliability requirements for the proposed application. Before any cells are adopted for your battery application they should undergo thorough qualification testing to identify any potential weaknesses. For more information see Battery Testing. If you don't have the necessary equipment to carry out these tests your friendly pack designer should be able to do it for you.

Manufacturing processes out of control

This is an area where the applications engineer can begin to have some influence. A cell may be well designed, but once it gets out of the design lab and into the factory its fate is determined by the factory manager. In well managed companies this should not be a problem, but a badly run production facility can introduce numerous potential failure sources into the cell. This is less likely to be a problem in a large automated plant with a well known brand name to protect, but if you are looking for the lowest cost cell manufacturer you need to be conscious that corners may be cut to achieve the cost targets. Some symptoms to watch out for:-

- Manual production methods. - It is very difficult to achieve precision and repeatability using manual assembly methods and lack of precision means potential short circuits, leaks, unreliable connections and contamination. This doesn't just apply to back street operations using low cost labour. Even with well managed companies, when new technologies are introduced, the initial customer requirements are usually supplied by hand made products or products made on semi automated machinery until the demand is established and the investment in automated production machinery is justified.

- Out of tolerance components create similar problems as with imprecise assembly noted above
- Burrs give rise to short circuits.
- Voids reduce cell capacity, increase impedance and impede heat dissipation
- Contamination of the active chemicals gives rise to unwanted chemical effects which could result in various forms of cell failure such as overheating, pressure build up, reduced capacity, increased impedance and self discharge and short circuits.
- Process out of control. - A typical example is variable coating thicknesses of the active chemicals on the electrodes. Once again the results could affect cell capacity, impedance and self discharge. Process control also applies to the temperature and humidity of the air in the production plant as well as to the dimensional accuracy of the components.
- Use of unapproved alternative materials. This is not necessarily obvious but it certainly happens. Tests on samples may be needed to verify this.
- Weld/sealing quality - This can result in poor, unreliable connections and localised heat build up.
- Mechanical weaknesses. In smaller cells the most likely problem will be leakage of the electrolyte. Larger cells will be more prone to cracking or splitting, which also cause leakage, or distortion which means the cells may not fit into the enclosure designed for them.
- Poor sealing results in leakage and loss of active chemicals and potential safety problems.
- Quality systems and quality management. - After the design of the cell itself, these are perhaps the most important factors affecting cell failures. The manufacturing facility needs to have in place, at key points in the production process, controls which set limits to, and monitor continuously , all the parameters which can ultimately affect the quality and reliability of the product. Corrective actions should come into play automatically whenever the specified limits are approached to ensure they are never breached. Not only should the system be in place but it should be seen to be fully operational. Records should be kept as evidence that the system is at all times operating correctly.

All of these points can be verified by the battery applications engineer to give confidence in the proposed cell supplier provided the cell suppliers allow access to their manufacturing plants.

See also Battery Manufacturing

Ageing

Battery performance gradually deteriorates with time due to unwanted chemical reactions and physical changes to the active chemicals. This process is generally not reversible and eventually results in battery failure. The following are some examples:-

- Corrosion consumes some of the active chemicals in the cell leading to increased impedance and capacity loss
- Chemical loss through evaporation. Gaseous products resulting from over charging are lost to the atmosphere causing capacity loss.

- Change in physical characteristics (morphology) of the working chemicals.
    - Crystal formation. Over time the crystal structure at the electrode surface changes as larger crystals are formed. This reduces the effective area of the electrodes and hence their current carrying and energy storage capacity.
    - Dendritic growth. This is the formation of small crystals or treelike structures around the electrodes in what should be an aqueous solution. Initially these dendrites may cause an increase in self discharge. Ultimately dendrites can pierce the separator causing a short circuit.
- Passivation. This is a resistive layer which builds up on the electrodes impeding the chemical action of the cell.
- Shorted cells. Cells which were marginally acceptable when new may have contained latent defects which only become apparent as the ageing process takes its toll. This would include poor cell construction, contamination, burrs on metal parts which can all cause the electrodes to come into contact with each other causing a short circuit.
- Electrode cracking Some solid electrolyte cells such as Lithium polymer can fail because of cracking of the electrolyte

The ageing process outlined above is accelerated by elevated temperatures.

Uncontrolled operating conditions

Good batteries are not immune to failure which can be provoked by the way they are used or abused. High cell temperature is the main killer and this can be brought about in the following situations.

- Bad applications design
- Unsuitable cell for the application
- Unsuitable charging profile
- Overcharging
- Environmental conditions. High ambient temperatures. Lack of cooling.
- High storage temperature
- Physical damage is also a contributing factor

Most of these conditions result in overheating of the cell which is what ultimately kills it.

Abuse

Abuse does not just mean deliberate physical abuse by the end user. It also covers accidental abuse which may be unavoidable. This may include dropping, crushing, penetrating, impacts, immersion in fluids, freezing or contact with fire, any of which could occur to an automotive battery for instance. It is generally accepted that the battery may not survive all these trials, however the battery should not itself cause an increased hazard or safety problem in these circumstances.

How Cells Fail

The actions or processes outlined above cause the cells to fail in the following ways:

Active chemicals exhausted

In primary cells this is not classed as a failure since this is to be expected but with secondary cell we expect the active chemicals to be restored through recharging. As noted above however ageing will cause the gradual depletion of the active mass.

Change in molecular structure

Even though the chemical composition of the active chemicals may remain unchanged, changes in their morphology which take place as the cell ages can impede the chemical actions from taking place, ultimately rendering the cell unusable.

Breakdown of the electrolyte

Overheating or over-voltage can cause chemical breakdown of the electrolyte.

Electrode plating

In Lithium cells, low temperature operation or over-current during charging can cause deposition of Lithium metal on the anode resulting in irreversible capacity loss and eventually a short circuit.

Increased internal impedance

The cell internal impedance tends to increase with age as the larger crystals form, reducing the effective surface area of the electrodes.

Reduced capacity

This is another consequence of cell ageing and crystal growth. Is is sometimes recoverable through reconditioning the cell by subjecting the cell to one or more deep discharges.

Increased self discharge

The changing crystal structure of the active chemicals as noted above can cause the electrodes to swell increasing the pressure on the separator and, as a consequence, increasing the self discharge of the cell. As with all chemical reactions this increases with temperature.
Unfortunately these changes are not usually reversible.

Gassing

Gassing is generally due to over charging. This leads to loss of the active chemicals but In many cases this can also be dangerous. In some cells the released gases may be explosive. Lead acid cells for instance give off oxygen and hydrogen when overcharged.

Pressure build up

Gassing and expansion of the chemicals due to high temperatures lead to the build up of pressure in the cell and this can be dangerous as noted above. In sealed cells it could lead to the rupture or explosion of the cell due to the pressure build up unless the cell has a release vent to allow the escape of the gasses.

Swelling

Before the pressure in the cell builds up to dangerous limits, some cells are prone to swelling due to overheating. This is particularly true of Lithium polymer pouch cells. This can lead to
problems in fitting the cell into the battery enclosure.

Overheating

Overheating is always a problem and is a contributing factor in nearly all cell failures. It has many causes and it can lead to irreversible changes to the chemicals used in the cells, gassing, expansion of the materials, swelling and distortion of the cell casing. Preventing a cell from overheating is the best way of extending its life.

Penetration of the separator

Short circuits can be caused by pentration of the separator due dendrite growth, contamination, burrs on the electrodes or softening of the separator due to overheating.

Thermal runaway

The rate at which a chemical action proceeds doubles for every 10°C increase in temperature. The current flow through a cell causes its temperature to rise. As the temperature rises the electro-chemical action speeds up and at the same time the impedance of the cell is reduced leading to even higher higher currents and higher temperatures which could eventually lead to destruction of the cell unless precautions are taken.

Consequences of Cell Faults

The failure mechanisms noted above to not always lead to immediate and complete failure of the cell. The failure will often be preceded by a deterioration in performance. This may be manifest in reduced capacity, increased internal impedance and self discharge or overheating. If a degraded cell continues in use, higher cell heat dissipation may result in premature voltage cut off by the protection circuits before the cell is fully charged or discharged reducing the effective capacity still further.

Measurement of the State of Health of the cells can provide an advance warning of impending failure of the cell.

There are several possible failure modes associated with the complete breakdown of the cell, but it is not always possible to predict which one will occur. It depends very much on the circumstances.

- Open circuit - This is a fail safe mode for the cell but may be not for the application. Once the current path is cut and the battery is isolated, the possibility of further damage to the battery is limited. This may not suit the user however. If one cell of a multicell battery goes open circuit then the whole battery will be out of commission.
- Short circuit - If one cell of a battery chain fails because of a short circuit, the rest of the cells may be slightly overloaded but the battery will continue to provide power to its load. This may be important in emergency situations.
  Short circuits may be external to the cell or internal within the cell. The battery management system (BMS) should be able to protect the cell from external shorts but there's not much the BMS can do to protect the cell from an internal short circuit.
  Within the cell there are different degrees of failure.
    - Hard Short
      Solid connection between electrodes causes extremely high current flow and complete discharge resulting in permanent damage to the cell
    - Soft Short
      Small localised contact between electrodes. Possibly self correcting due to melting of the small regions in contact caused by the high current flow which in turn interrupts the current path as in a fuse.
- Explosion - This is to be avoided at all costs and the battery must incorporate protection circuits or devices to prevent this situation from occurring.
- Fire - This is also possible and as above the battery should be protected from this possibility.

False Alarms

Occasionally you may find that an apparent fault in the battery is actually a fault external to the cells. It could be in the charger or in the protection circuitry. This may occur when a "perfectly good" charger is unable to charge the battery. It is possible that this could be caused by a mismatch in the protection limit settings between the battery and the charger. The charger voltage regulation may not have the range to cope with a fully discharged battery or the current limits may be set too low to allow the initial current inrush into the battery when the charger is switched on.
It is also possible that a fault in the protection circuit could cause the battery to discharge. The possibility of external faults should therefore be verified before the cells are blamed.

Maximising Battery Life

Applications design

The first step is to ensure that the most appropriate battery is chosen for the application.

Supplier qualification

The second step is to select a cell supplier who can be relied upon to provide a safe reliable product.

Cell qualification

The next step is to verify that the chosen cells meet the desired specification under every expected condition of use and that inbuilt safety devices such as pressure vents function correctly.

Protection circuits

Once the cell has been chosen the ancillary electronic circuits can be specified. The most important of these are the safety circuits which ensure that the cells are maintained within their specified operating temperature, current, and voltage limits. This should also include the specification of the charger.

See Battery Protection Methods

Product qualification

When finished battery packs become available, they should be subject to qualification tests as stand alone units and as part of the qualification testing of the product in which they are used and also with the associated charger. These tests should identify whether there are any undesired interactions between these units.

Storage

Don't use up the battery's life unnecessarily by storing it at too high temperatures.

Manufacturing

After taking such care during the design process, don't let the pack manufacturing introduce potential faults into the battery. Make sure that the factory is implementing the necessary quality systems.

Planned maintenance

Provide the user with recommended operating and maintenance procedures for the battery (including reconditioning if this is possible) and ways of monitoring the battery State of Health.

See also Lithium Battery Failures

For more information see Battery Life

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Battery Safety

Batteries have the potential to be dangerous if they are not carefully designed or if they are abused. Cell manufacturers are conscious of these dangers and design safety measures into the cells. Likewise, pack manufacturers incorporate safety devices into the pack designs to protect the battery from out of tolerance operating conditions and where possible from abuse. While they try to make the battery foolproof, it has often been explained how difficult this is because fools can be so ingenious. Once the battery has left the factory its fate is in the hands of the user. It is usual to provide "Instructions For Use" with battery products which alert the end user to potential dangers from abuse of the battery. Unfortunately there will always be perverse fools who regard these instructions as a challenge.

Warning

Subjecting a battery to abuse or conditions for which it was never designed can result in uncontrolled and dangerous failure of the battery. This may include explosion, fire and the emission of toxic fumes.

We are helped in assessing what hazards to protect against, and the degree of protection required, by the publication of national standards. Some of these are listed in the section on Standards. Typical safety test requirements are outlined in the section on Testing.

"Designed in" safety measures

These are not something that the battery applications engineer can control but they could influence the choice of cells to be specified for a particular application.

- Cell chemistry - In the quest for ever higher energy and power densities cell makers have utilised ever more reactive chemical mixes, but these highly reactive properties which are needed to provide the higher energy densities are likely to increase the risk of danger in case of cell failures. For safety reasons the cell maker may compromise on the maximum power by using a less reactive chemical mix or by introducing some form of chemical retardant in order to reduce the risk of fire or explosion if a cell suffers physical damage. As an example, the original Lithium-ion cells were a Lithium Cobalt combination and these provide maximum power, however Lithium Manganese cells which have a slightly lower power rating are now the preferred choice for many applications because they are inherently safer if damaged.
- Electrolytes - Chemical inhibitors are often added to electrolytes to make them self extinguishing or flame retarding in case of abuse of the cell which could lead to fire.
- Cell construction - Low power cells have relatively simple mechanical structures which have undergone many years of development and cell failures caused by poor mechanical design a very rare. For high power cells however, thermal design can be a source of weakness. Getting

the excess heat out of the cell can be a problem and poor designs can result in localised hotspots within the cell which can cause cell failure. Good thermal performance for high power cells requires substantial current paths.

- Separators - If for any reason a cell overheats, this can cause the separators, which are typically made of plastic, to distort or melt. In the worst case this could lead to a short circuit between the electrodes with even more serious consequences. Internal short circuits can also occur due to dendrite or crystal growth on the electrodes. External circuits can not protect against an internal short circuit and various separators have been designed to avoid this problem. These include rigid separators which do not distort even under extreme temperature conditions, flexible ceramic coated plastic which prevents contact between the electrodes and "shut down separators" with special plastic formulations, similar to a resettable fuse, whose impedance suddenly increases when certain temperature limits are reached.

  Once an internal short occurs there is not much that can be done by external measures to protect the battery. Such an occurrence can be detected by a sudden drop in the cell voltage and this can be used to trigger a cut off device to isolate the battery from the charger or the load. While it does not solve the problem at least it prevents external events from making it any worse. Fortunately an internal short circuit is a rare occurrence.

  The likelihood of an internal short circuit occurring can be minimised by keeping the cell temperature within limits and this should be the user's first line of defence.
- Robust packaging - As with cell construction this is unlikely to be a source of problems.
- Circuit Interrupt Device (CID) - Some cells also incorporate a CID which interrupts the currrent if the internal gas pressure in the cell exceeds specified limits.
- Safety vents - If other safety devices fail and a cell is allowed to overheat, chemical reactions can result in gassing and the active materials will also expand due to the temperature rise. This can cause a dangerous build up of pressure inside the cell which could result in rupture of the case or even an explosion. Safety vents are needed as a final safety precaution to release the pressure before it reaches a dangerous level. Automatic release guard vents prevent the absorption of external air into the cell but allow controlled release of excess internal pressure to avoid leakage and prevent uncontrolled rupture of the cell case.
- Keyed and shrouded connectors or terminals - These are designed to protect the operator, to prevent accidental short circuits and the connection of incorrect loads or chargers to the battery. See Battery Pack Design (External connections)
- All the designed-in safety precautions can be worthless if the manufacturing processes are not controlled properly. Burrs on the electrodes, misaligned or out of tolerance components, contaminated electrode coatings or electrolytes can all cause short circuits or penetration of the separator. A short circuit caused by a microscopic metallic particle may simply cause cause local overheating or an elevated self discharge rate due to a relatively high impedance current path between the electrodes, but a direct short circuit due to penetration of the separator by a burr on the electrode can lead to excessive overheating and eventually thermal runaway of the cell.

External Safety Devices

Protecting the cell from out of limits operating conditions, either from the loads imposed by the intended application or abuse by the user or from unsuitable charging regimes, is the job of the battery pack designer.

Heat is the biggest killer of batteries and this is most likely to be due to unsuitable charging methods or procedures. But chargers are not the only culprits. Overloading the cell during discharge also causes overheating. Many safety devices are therefore based on sensing the cell temperature and isolating the cell from its load or from the charger if the temperature reaches dangerous levels.

See the section on Chargers for more information about safe charging.

Heat damages a cell no matter what its source and a cell will suffer the same damage by being placed in a high ambient temperature environment as it would from improper use. There is no practical way to protect the cell from this kind of abuse. (Sounding an alarm could be a possibility)

Apart from damage from overheating, a battery may be damaged from excessive currents and from over and under voltage. Suitable protection methods and how they are implemented are described in detail in the section Battery Protection Methods

Short Circuits and their Consequences (What can a Joule do?)

Short circuiting a capacitor or a battery is definitely not recommended as the destructive power unleashed is often seriously under estimated.

As an example, a 0.1Farad capacitor charged to 14 Volts will store 10 Joules of energy **($E = ½ CV^2$)**. This may not seem very much, it is only 10 Watt seconds, but it is enough to punch a hole through aluminium foil creating a lot of sparks. 30 Joules is enough to weld a wire to a ball bearing. This is because the discharge period is very short, almost instantaneous, resulting in a power transfer of hundreds of watts.

Batteries store even more energy. For comparison, a fully charged 3.6 Volt, 1000 mAh mobile phone battery has a low internal impedance and contains 12,960 Joules of energy. Short circuiting these cells can cause extremely high currents and temperatures within the cell resulting in the breakdown of the chemical compounds from which it is made. This in turn can cause the rapid build up of pressure within the cell resulting in its catastrophic failure, with unpredictable consequences including the uncontrolled rupture of the cell or even fire.

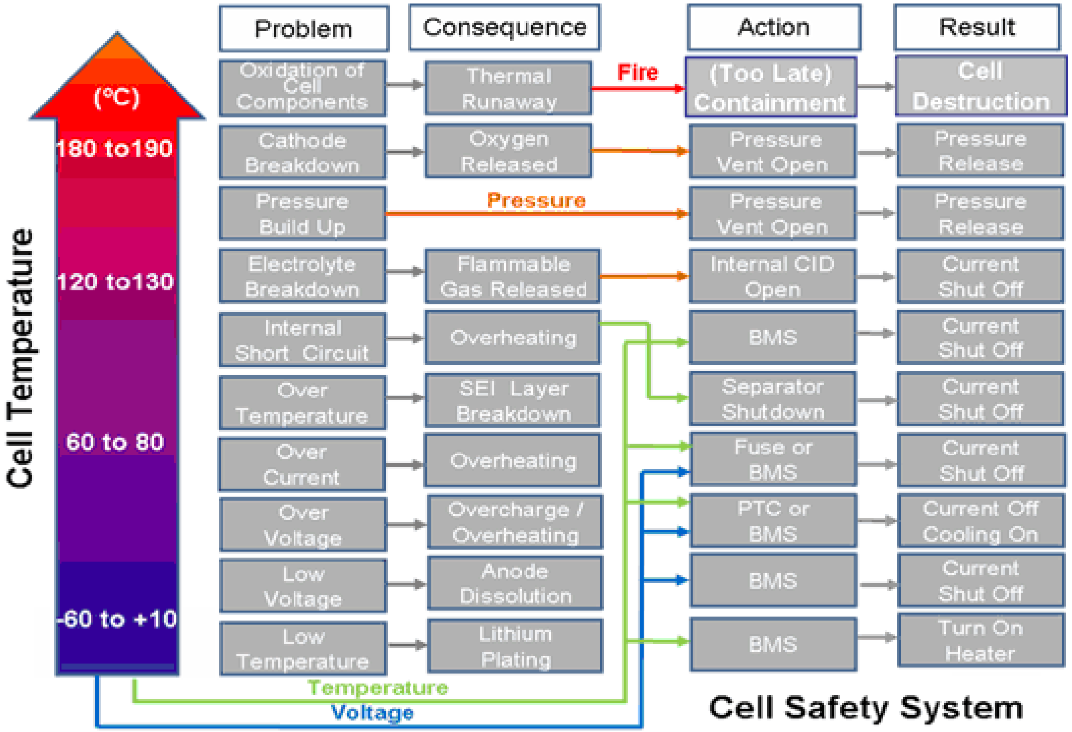
By the same token, a single, fully charged 200 Ah, 3.6 Volt Lithium Ion automotive cell (or the similar capacity from any other cell chemistry) contains 2,592,000 Joules of energy. Don't wait around to see what happens if you drop a wrench on the terminals!!

YOU HAVE BEEN WARNED

Battery (and User) Protection System

The diagram below summarises the types of problems which can occur in Lithium energy cells and their consequences together with the actions which may be taken by the Battery Management System (BMS) to address the problems and the results of the actions.

Cell Protection Mechanisms



Multi Level Battery Safety Plan

The responsibility for battery safety starts at the cell maker's premises and continues through to the design af the battery application. A multi-level safety plan should include consideration of at least the following components.

Supplier and production audit

- Cell design audit
- Manufacturer's technical capability
    - Staff (Engineering, Management)
    - Facilities (Materials analysis capability)
- Manufacturer's quality systems.
- Process controls. (In place and being implemented)

Cell level safety devices

- CID (Circuit Interrupt Device)
- Shut down separator
- Pressure vent

External circuit devices

- PTC resistors (Low power only)
- Fuses
- Cell and battery isolation to prevent event propagation
  - Electrical (Contactors)
  - Physical (Separation, barriers)

BMS Software

- Monitoring of all key indicators coupled to control actions.
- (Cooling, Power disconnect)

BMS Hardware

- Fail safe back-up Hardware switch off in case of software failure. Set to slightly higher limits
- Battery switch off in case low voltage BMS power supply or other system component fails

Automotive High Voltage High Capacity Batteries

Concerns are often expressed about the safety of high power automotive batteries if they are damaged or crushed in an accident. Such batteries are normally subject to stringent safety testing before they may be approved for use and a range of International Standards has been developed for this purpose.

Nevertheless batteries in general present a lower hazard in the case of an accident than a full tank of petrol.

The dangers don't just come from the chemical content of the batteries. High capacity batteries store an immense amount of energy which can cause enormous damage if the battery is short circuited.

HANDLE WITH CARE.

Handling Instructions

User Safety Precautions

These are intended to protect the user as well as the battery. Detailed recommendations for handling and using batteries are given in the section on User Safety Instructions

MSDS Material Safety Data Sheets

Material Safety Data Sheets are designed to provide safety information about any physical or chemical hazard associated with a particular product and procedures for handling or working with hazardous material content. They are intended for employers, employees and emergency services responsible for dealing with fire or medical emergencies.

MSDS's are specific to individual products or classes of products and include information such as the chemical composition of each of the chemicals used and physical data (melting point , boiling point , flash point etc.) as well as the reactivity, toxicity, flammability, health effects, recommended first aid, storage, disposal, protective equipment and procedures to follow in case of a fire, spill or leak.

In the case of batteries, the information is usually provided by the cell manufacturer since they control the contents of the product.

See MSDS for an example of a typical data sheet for Lithium cells used in mobile phones.

See also Battery Death for dangerous operating practices which could damage the battery and Electric Shocks for an outline of potential hazards to the user when working with batteries.

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Low Power Batteries (Less than 5Ah)

Design Considerations

Low power batteries are usually made in very large volumes and low cost is usually the most important design goal. A wide range of primary and secondary cells is available to satisfy this need. The range of Cell Chemistries employed is fairly small but the range of available Cell Packaging is very wide.

For fifty years the lowest cost, low drain applications have been powered by Primary Cells and the market is well served by a range of standard low cost Leclanché and Alkaline cells. In the last twenty years however the explosion of applications requiring cordless power such as mobile phones, power tools, laptop computers and PDAs has created a demand for Secondary Cells to supply the higher current drains and to provide the convenience of recharging that these new applications require. (It could also be said that it is the availability of new battery technologies and new

Cell Chemistries which has made these applications possible.)

Cost and capacity are not the only considerations in determining the choice of battery technology. Small size is usually also an important design goal and the ergonomic design of these products determines the shape, size and weight and even the colour of the battery which can be used. These requirements have given rise to a demand for Battery Pack Designs in which standard secondary cells are incorporated into custom battery packs to satisfy particular product or market needs. Battery specification is no longer as simple as it used to be.

See also High Power Batteries

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High Power Batteries (More than 5Ah)

Some batteries need to be "Bomb Proof"

Design Considerations

For low power applications such as mobile phones or power tools where the typical cost of a battery may be £10 or less, batteries are often considered as consumables and battery maintenance is not usually a high priority. But for high power Traction Applications such as electric vehicles (EVs) and hybrid electric vehicles (HEVs) where batteries may cost thousands of pounds, maximising the Battery Life becomes a major design objective.

Battery designs may be optimised for capacity or for power handling capability, often called "rate". For example, in EV applications, range is most important and so they use high capacity batteries. HEVs on the other hand require smaller batteries which can provide a high instantaneous power boost and they use high rate batteries. The section on Cell Construction explains the design trade-offs involved.

Deep cycle batteries are designed to be discharged down to as much as 80% depth of discharge time after time, and have much thicker plates that a standard automotive battery.

Many high power batteries are also used in safety critical applications or for providing emergency power. The overriding design goal is that they should be able to deliver their specified power whenever they are called upon to do so. For this the user needs to be able to monitor the condition of the battery (known as the State of Health) at any time and to be have available tools and procedures to maintain the battery in top working condition.

In many applications high power batteries also generate excessive heat and Thermal Management also becomes a necessary design consideration. In the quest to get the maximum energy storage or maximum power delivery from practical battery installations many novel Cell Chemistries have been developed. These are almost always secondary cells, but some single use batteries have been developed for emergency or military applications.

Because of their high energy content the consequences of failure of these cells can be very dangerous. See the section on Safety for an indication of the destructive power of a shorted cell.
Safety considerations should therefore be high on the designer's priority list.

See also Low Power Batteries

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Battery Testing

Testing is designed to tell us things we want to know about individual cells and batteries.

Some typical questions are:

- Is it fully charged ?
- How much charge is left in the battery ?
- Does it meet the manufacturer's specification ?
- Has there been any deterioration in performance since it was new ?
- How long will it last ?
- Do the safety devices all work ?
- Does it generate interference or electrical noise ?
- Is it affected by interference or electrical noise ?

The answers are not always straightforward.

Indirect Measurements

Although all of the cell parameters the design engineer may wish to measure can be quantified by direct measurement, this is not always convenient or possible . For example the amount of charge left in the battery, the State of Charge (SOC) can be determined by fully discharging the battery and measuring the energy output. This takes time, it wastes energy, each test cycle shortens the battery life and it may not be practical if the battery is in use. It would also be pointless for a primary cell. For more detailed information of how this is done see the State of Charge page.

Similarly, the remaining life of a secondary cell can be determined by continuously cycling it until it fails, but there's no point in knowing the cell life expectation if you have to destroy it to find out. This is known as the State of Health (SOH) of the battery.

What is needed are simple tests or measurements which can be used as an approximation to, or indirect measure of, the desired parameter. For more information see the State of Health page

Test Conditions

In all of the following tests, and testing in general, the test conditions must be specified so that repeatable results can be obtained, and meaningful comparisons can be made. This includes factors such as method, temperature, DOD, load and duty cycle. For instance the cell capacity and cycle life, two key performance indicators could vary by 50% or more depending on the temperature and the discharge rate at which the tests were carried out. See also cell Performance Characteristics.

Battery specifications should always include the test conditions to avoid ambiguity.

Qualification Testing

Qualification testing is designed to determine whether a cell or battery is fit for the purpose for which it was intended before it is approved for use in the product. This is particularly important if the cell is to be used in a "mission critical" application. These are comprehensive tests carried out initially on a small number of cells including testing some of them to destruction if necessary. As a second stage, qualification also includes testing finished battery packs before the product is approved for release to the customer. The tests are usually carried out to verify that the cells meet the manufacturer's specification but they could also be used to test the cells to arbitrary limits set by the applications engineer to determine how long the cells survive under adverse conditions or unusual loads, to determine failure modes or safety factors.

The battery packs should also be tested with the charger recommended for the application to ensure compatibility. In particular the potential user patterns must be evaluated to ensure that the batteries do not become inadvertently overcharged. See also the section on Chargers.

Shake and Bake

- **Mechanical Testing**

  Typical tests are included in the safety standards below. They include simple tests for dimensional accuracy to dynamic testing to verify that the product can survive any static and dynamic mechanical stresses to which it may be subject.

- **Environmental Testing**

  Typical tests are included in the safety standards below. They are designed to exercise the product through all the environmental conditions likely to be encountered by the product during its lifetime.

Abuse Testing

The purpose of abuse testing is to verify that the battery is not a danger to the user or to itself either by accidental or deliberate abuse under any conceivable conditions of use. Designing foolproof batteries is ever more difficult because as we know, fools are so ingenious.
Abuse testing (always interesting to witness) is usually specified as part of the Safety Testing (below). Recent accidents with Lithium cells have highlighted the potential dangers and stricter battery design rules and a wider range of tests are being applied as well as stricter Transport Regulations for shipping the products.

Safety Standards

Consumer products normally have to comply with national or international Safety Standards required by the safety organisations of the countries in which the products are sold. Examples are UL, ANSI, CSA and IEC standards.

Typical contents

Safety Tests

Casing

- Strength, rigidity and flammability
- Mould stress (Temperature)
- Venting
- Insulation
- Electrolyte not under pressure
- No leakage
- No explosion or fire risk

Protection from or tolerance to

- Short circuit
- Overcharge (time)
- Overcharge (voltage)
- Over-discharge
- Voltage reversal
- High temperature
- Low temperature
- Misuse
- Abuse

Power output - Load test

Failsafe electronics

Marking

Instructions for use

Safety instructions

Mechanical tests

- Crush tests
- Nail penetration tests
- Shock test
- Vibration test
- Impact test
- Drop test

Environmental tests

- Heating
- Temperature cycling
- Altitude
- Humidity
- Exposure to fire

The published safety standards specify the method of testing and the limits with which the product must comply.

DEF Standards

Cells used in military applications usually have to meet more stringent requirements than those used in consumer products.

Cycle testing

This is perhaps the most important of the qualification tests. Cells are subjected to repeated charge - discharge cycles to verify that the cells meet or exceed the manufacturer's claimed cycle life. Cycle life is usually defined as the number of charge - discharge cycles a battery can perform before its nominal capacity falls below 80% of its initial rated capacity. These tests are needed to verify that the battery performance is in line with the end product reliability and lifetime expectations and will not result in excessive guarantee or warranty claims.

Temperature, charge/discharge rates and the Depth of Discharge each have a major influence on the cycle life of the cells (See the page on Cycle Life) Depending on the purpose of the tests, the temperature and the DOD should be controlled at an agreed reference level in order to have repeatable results which can be compared with a standard. Alternatively the tests can be used to simulate operating conditions in which the temperature is allowed to rise, or the DOD restricted, to determine how the cycle life will be affected.

Similarly cycle life is affected by over charging and over discharging and it is vital to set the correct voltage and current limits if the manufacturer's specification is to be verified.

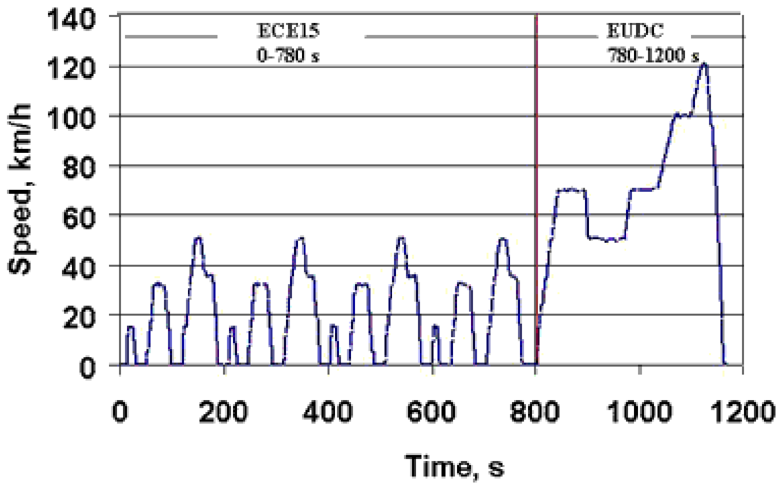
Cycle testing is usually carried out banks of cells using multi channel testers which can create different charge and discharge profiles including pulsed inputs and loads. At the same time various cell performance parameters such as temperature, capacity, impedance, power output and discharge time can be monitored and recorded. Typically it takes about 5 hours for a controlled full charge discharge cycle. This means testing to 1000 cycles will take 208 days assuming working 7 days per week 24 hours per day. Thus it takes a long time to verify the effect of any ongoing improvements made to the cells. Because the ageing process is continuous and fairly linear, it is possible to predict the lifetime of a cell from a smaller number of cycles. However to prove it conclusively in order to guarantee a product lifetime would require a large number of cells and a long time. For high power batteries this could be very expensive.

Load testing

Load testing is used to verify that the battery can deliver its specified power when needed.
The load is usually designed to be representative of the expected conditions in which the battery may be used. It may be a constant load at the C rate or pulsed loads at higher current rates or in the case of automotive batteries, the load may be designed to simulate a typical driving pattern. Low power testing is usually carried out with resistive loads. For very high power testing with variable loads other techniques may be required. A Ward-Leonard controller may be used to provide the variable load profile with the battery power being returned to the mains supply rather than being dissipated in a load.

Note that the battery may appear to have a greater capacity when it is discharged intermittently than it may have when it is discharged continuously. This is because the battery is able to recover during the idle periods between heavy intermittent current drains. Thus testing a battery capacity with a continuous high current drain will not necessarily give results which represent the capacity achievable with the actual usage profile.

Load testing is often required to be carried out with variable load levels. This may simply be pulsed loads or it could be more complex high power load profiles such as those required for electric vehicle batteries. Standard load profiles such as the Federal Urban Driving Schedule (FUDS) and the Dynamic Stress Test (DST) specified by the United Sates Advanced Battery Consortium (USABC), in the USA, and the United Nations Economic Commission for Europe specification (ECE-15) and the Extra Urban Driving Cycle (EUDC) in Europe have been developed to simulate driving conditions and several manufacturers have incorporated these profiles into their test equipment.



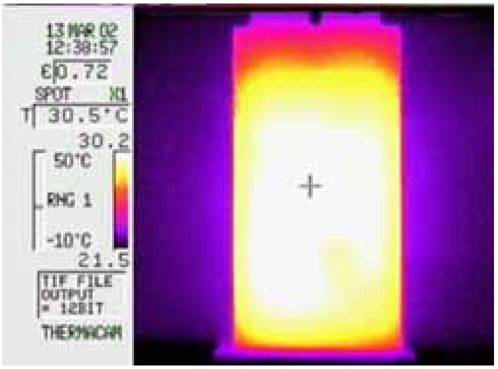
ECE-15 Simulated Driving Cycle

While these standard usage cycles have been developed to provide a basis for comparison, it should be noted that the typical user doesn't necessarily drive according to these cycles and is likely to accelerate at least twice as fast as the allowed for in the standards.

Calorimetry

Battery thermal management is critical for high-power battery packs. Obtaining accurate heat generation data from battery modules is essential for designing battery thermal management systems. A calorimeter is used to quantify the total amount of heat generated by the battery while it is cycled through its charge/discharge cycles. This is essentially an insulated box into which the battery is placed which captures and measures the heat generated the battery during cycling. The system is calibrated by comparing the heat generated by the battery with the heat generated by a known heat source.

Thermal imaging



Thermal imaging is used to check for "hot spots" which would indicate points of high thermal stress in the cell or the battery pack. It is a photographic technique which records the intensity of the infra red radiation emitted by a subject using a special camera. The image on the left is of a lithium ion pouch cell after a prolonged discharge at 4C. In this case the temperature is evenly distributed within the cell and the cell terminals are running cool. These tests can help to identify problems such as overheating, inadequate heat sinking or air flow, undersized current conductors and interference from neighbouring cells or devices. The images can also be used to determine the best location for the temperature sensors used in protection circuits.

Electromagnetic Compatibility (EMC) testing

Electromagnetic compatibility (EMC) is the ability of electronic and electrical equipment and systems to operate without adversely affecting other electrical or electronic equipment OR being affected by other sources of interference such as power line transients, radio frequency (RF) signals, digital pulses, electrical machinery, lightning, or other influences.

Note that EMC concerns both the emission of electromagnetic interference (EMI or radio frequency interference RFI) by a product or device and the product's susceptibility to EMI emitted from other sources. The interference may be conducted through power or signal cables or the chassis of the equipment, it may be propagated through inductive or capacitive coupling or it may be radiated through the atmosphere.

Just because batteries are DC devices we can not assume that they are immune from EMC problems. At MPower we have seen the battery protection circuitry in a two way radio disabled by RF interference from the handset's transmitter. Similar problems are possible in automotive applications where the power cabling is notoriously noisy due to interference from the ignition systems and transients from electric motors and switches. While the battery itself may not emit RF interference, the same can not be said of the charger. Many chargers use switch mode regulators which are also notorious for emitting electrical noise. Radiated EMI can be critical to such applications as heart pacemakers, medical instrumentation, communications equipment and military applications.

As with many problems prevention is better than cure and it is wise to start considering EMC at the earliest possible stage of the design to avoid costly design changes when the project is submitted for final approval. This may involve system design choices such as operating frequencies, circuit layouts and enclosure design and the avoidance of designs with high transient currents.

Various techniques are used to minimise the effects EMI. Sensitive parts of the circuit may be physically separated from sources of interference, the equipment may be enclosed in a sealed metal box, individual parts of the circuits may be shielded with metal foil, filters can be added to cables to filter out the noise,

EMC testing involves specialised test equipment and facilities. Testing must be carried out in an environment free from other sources of EMI. This usually means an anechoic chamber or a Faraday cage. Special wide range signal sources and sensitive receivers are needed to generate and measure the interference.

Some examples of EMC requirements are give in the section on Standards

Process audits

Conducting a process audit of the cell manufacturer's production facilities is further way of gaining confidence in the cells under consideration however this option is usually available only to major purchasers of high volume or high cost cells. Unless you are one of these you will have to rely on your friendly pack maker who possibly qualifies for special treatment.

The process audit involves verifying that the cell maker has appropriate quality systems in place and that these are being fully implemented at every stage of the manufacturing process. To be effective this task needs to be conducted by a team with specialist industry knowledge. Again this is a job best left to your pack maker who should have the necessary experience and credibility with the cell makers.

Inspection and Production Testing

The purpose of inspection production testing is to verify that the cells which have been purchased and the products built with them conform to agreed specifications. These tend to be short tests carried out on 100% of the throughput or on representative samples. The composition of the materials from which the components are made should not be overlooked. We have seen examples of unscrupulous suppliers plating connectors with a gold coloured alloy rather than the gold specified and using cheap plastics which buckle in the heat rather than the high quality plastics required.

Typical tests include both mechanical and electrical tests. The components are checked for dimensional accuracy and sample subassemblies are subject to weld strength testing of the interconnections. Electrical parameters measured include the internal impedance and the output voltage of the cell or battery pack with or without a load. The battery is also submitted to short duration charging and discharging pulses of about 2 milliseconds to check that the unit accepts and can deliver charge.

Battery packs are normally subjected to more comprehensive testing to ensure that the electronics are functioning correctly. The protection circuit is checked by applying a short circuit across the battery terminals for 1 or 2 seconds and checking that the current path is cut within the prescribed period and that the battery recovers afterwards. The output of the fuel gauge is checked and if the battery has built in memory, the data such as cell chemistry code, date and serial number are read out and recorded to permit traceability.

Charge conditioning or Formation

This is normally carried out by the cell manufacturer but in some circumstances it could be the responsibility of the battery pack assembler. In any case the cells must be tested to ensure that they are ready to deliver current.

Performance Monitoring

Performance monitoring is used to verify whether the cell is continuing to perform as required once it is in use in the application for which it was specified. These are individual tests specified by t he user.

There are no simple direct measurements, such as placing a voltmeter across the terminals, to determine the condition of the battery. The voltmeter reading may tell us something about the state of charge (with an enormous margin of error), but it cannot tell us how well the battery will deliver current when demanded.

Internal Resistance

It is necessary to know the internal resistance of the cell in order to calculate the Joule heat generation or I^2R power loss in the cell, however a simple measurement with an ohmmeter is not possible because the current generated by the cell itself interferes with the measurement.

To determine the internal resistance, first it is necessary to measure the open circuit voltage of the cell. Then a load should be connected across the cell causing a current to flow. This will reduce the cell voltage due to the IR voltage drop across the cell which corresponds to the cell's internal resistance. The cell voltage should then be measured again when the current is flowing. The resistance is calculated by ohms law from the voltage difference between the two measurements and the current which is flowing through the cell.

Open Circuit Voltage OCV

Measuring a battery's open circuit voltage is not a reliable measure of its ability to deliver current. As a battery ages, its internal resistance builds up. This will reduce the battery's ability to accept and to hold charge, but the open circuit voltage will still appear normal despite the reduced capacity of the battery. Comparing the actual internal resistance with the resistance of a new battery will provide an indication of any deterioration in battery performance.

State Of Charge (SOC)

For many applications the user needs to know how much energy is left in a battery. The SOC is also a fundamental parameter which must be monitored and controlled in Battery Management Systems. The methods of estimating the SOC are explained in the section on State Of Charge.

State Of Health (SOH)

The State of Health is a measure of a battery's ability to deliver the specified current when called upon to do so. It is an important factor for monitoring battery performance once it has entered into use. This is treated briefly in the section below and more fully in the section on State Of Health.

Impedance and Conductance Testing

The discussion about the battery equivalent circuit in the section on Performance Characteristics shows that we can expect the battery impedance to increase with age.

Battery manufacturers have their own definitions and conventions for Impedance and Conductance based on the test method used. Though not strictly correct they serve their purpose.

The test method involves applying a small AC voltage "E" of known frequency and amplitude across the cell and measuring the in phase AC current "I" that flows in response to it.

The Impedance "Z " is calculated by Ohm's Law to be Z=E/I

The Conductance "C" is similarly calculated as C=I/E (the reciprocal of the impedance)

Note that the impedance increases as the battery deteriorates while the conductance decreases. Thus C correlates directly with the battery's ability to produce current whereas Z gives an inverse correlation. The conductance of the cell therefore provides an indirect approximation to the State of Health of the cell. This measurement can be refined by taking other factors into account. These are outlined in the page about State of Health.

In addition to impedance and conductance these tests will obviously detect cell defects such as shorts, and open circuits.

These test methods can be used with different cell chemistries however different calibration factors must be built into the test equipment to take into account differences in the aging profiles of the different chemistries.

Impedance and conductance testing are reliable, safe, accurate, fast and they don't affect the battery performance. They can be carried out while the battery is in use or they can be used to continuously monitor the battery performance, avoiding the need for load testing or discharge testing.

DC measurements

Note that DC measurements do not recognise capacitance changes and therefore measurements of the internal resistance of the cell do not correlate so well with the SOH of the cell.

Using a conventional ohmmeter for measuring the resistance of the cables, contacts and inter-cell links is not satisfactory because the resistance is very low and the resistance of the instrument leads and the contacts causes significant errors. More accuracy can be achieved by using a Kelvin Bridge which separates the voltage measuring leads from the current source leads and thus avoids the error caused by the volt drop along the current source leads. See also charger voltage sensing.

Battery Analysers

Battery analysers are designed to provide an quick indication of the State of Health (SOH) of the battery. Some analysers also have the dual function of reconditioning the battery.

There are no industry standards for this equipment, mainly because there is no standard definition of State of Health. Each equipment manufacturer has their own favourite way defining and measuring it, from a simple conductance measurement to a weighted average of several measured parameters and the test equipment is designed to provide the corresponding answer. This should not be a problem if the same equipment is used consistently, however it does cause problems if equipment from different manufacturers is used to carry out the tests.

Failure Analysis

Cell failure analysis is best carried out by the cell manufacturers. Only they will have the detailed specifications of the cell mechanical and chemical components and it normally requires access to expensive analytical equipment such as electron microscopes and mass spectrometers which they should be expected to have. More information see Why Batteries Fail and Lithium Battery Failures

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Cell Chemistries

How Cells Work

Galvanic Action

In simple terms, batteries can be considered as electron pumps. The internal chemical reaction within the battery between the electrolyte and the negative metal electrode produces a build up of free electrons, ⊖ each with a negative charge, at the battery's negative (-) terminal - the anode. The chemical reaction between the electrolyte and the positive (+) electrode inside the battery produces an excess of positive (+) ions ⊕ (atoms that are missing electrons, thus with a net positive charge) at the positive (+) terminal - the cathode of the battery. The electrical (pump) pressure or potential difference between the + and - terminals is called voltage or electromotive force (EMF).

Different metals have different affinities for electrons. When two dissimilar metals (or metal compounds) are put in contact or connected through a conducting medium there is a tendency for electrons to pass from the metal with the smaller affinity for electrons, which becomes positively charged, to the metal with the greater affinity which becomes negatively charged. A potential difference between the metals will therefore build up until it just balances the tendency of the electron transfer between the metals. At this point the "equilibrium potential" is that which balances the difference between the propensity of the two metals to gain or lose electrons.

A battery or galvanic cell stores energy in chemical form in its active materials and can this convert this to electrical energy on demand, typically by means of an electrochemical oxidation-reduction (redox) reaction. (Note the generic name "redox" seems to have been appropriated by a recent flow battery design employing two vanadium redox couples).

Each galvanic or energy cell consists of at least three and sometimes four components

1. **The anode** or negative electrode (the reducing or fuel electrode) which gives up electrons to the external circuit and is oxidised during the elecrochemical (discharge) reaction. It is generally a metal or an alloy but hydrogen is also used. The anodic process is the oxidation of the metal to form metal ions.

   (LEO Lose Electrons - **Oxidation**)
2. **The cathode** or positive electrode (the oxidising electrode) which accepts electrons from the external circuit and is reduced during the electrochemical (discharge) reaction. It is usually an metallic oxide or a sulfide but oxygen is also used. The cathodic process is the reduction of the oxide to leave the metal.

   (GER Gain Electrons - **Reduction**). Remember the mnemonic of the lion growling.
3. **The electrolyte** (the ionic conductor) which provides the medium for transfer of charge as ions inside the cell between the anode and cathode. The electrolyte is typically a solvent containing dissolved chemicals providing ionic conductivity. It should be a non-conductor of

electrons to avoid self discharge of the cell.

4. **The separator** which electrically isolates the positive and negative electrodes.

The Discharge Process

When the battery is fully charged there is a surplus of electrons on the anode giving it a negative charge and a deficit on the cathode giving it a positive charge resulting in a potential difference across the cell.

When the circuit is completed the surplus electrons flow in the external circuit from the negatively charged anode which loses all its charge to the positively charged cathode which accepts it, neutralising its positive charge. This action reduces the potential difference across the cell to zero.

The circuit is completed or balanced by the flow of positive ions in the electrolyte from the anode to the cathode.

Since the electrons are negatively charged the electrical current they represent flows in the opposite direction, from the cathode (positive terminal) to the anode (negative terminal).

Two Electrolyte Systems

The principles of the Galvanic cell can be demonstrated by the workings of the Daniell cell, a two electrolyte system.

THE CATHODE

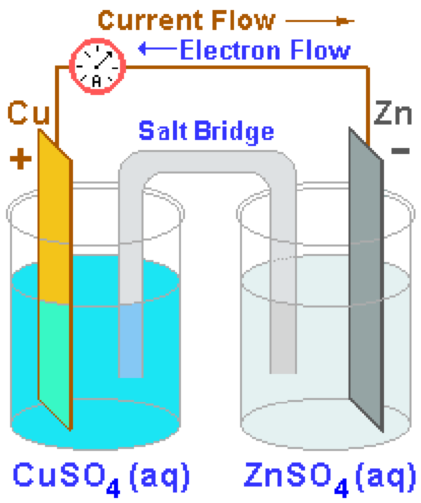
The **positive** pole of the battery

Accepts electrons from the external circuit

Copper metal deposits on the cathode

The site of **Reduction**

DANIELL CELL



THE ANODE

The **negative** pole of the battery

Zinc loses electrons more readily than copper

Supplies electrons to the external circuit

Zinc goes into aqueous solution

The site of **Oxidation**

The half-cell with the **highest** electrode potential	The half-cell with the **lowest** electrode potential
GER	**LEO**

Two electrolyte primary cell systems have been around since 1836 when the Daniell cell was invented to overcome the problems of polarisation. This arrangement illustrates that there are effectively two **half cells** at which the chemical actions take place. Each electrode is immersed in a different electrolyte with which it reacts. The **electrode potential**, either positive or negative, is the voltage developed by the single electrode. The electrolytes are separated from each other by a **salt bridge** or **porous membrane** which is neutral and takes no part in the reaction. By the process of osmosis, it allows the sulphate ions to pass but blocks the metallic ions.

This two electrolyte scheme allows more degrees of freedom or control over the chemical process.

Although more complex these cells enabled longer life cells to be constructed by optimising the electrolyte/electrode combination separately at each electrode.

More recently they have been employed as the basis for Flow Batteries in which the electrolytes are pumped through the battery, providing almost unlimited capacity.

Zinc is a very popular anode material and the chemical action above causes it to dissolve in the electrolyte.

The Daniell cell shown can be said to "burn zinc and deposit copper"

Note- The simple, single electrolyte cell can also be represented by two half cells. It can be considered a special case of a Daniell cell with the two electrolytes being the same.

The model of the cell as two half cells is used by electro-chemists and cell designers to calculate electrode potentials and and characterise the chemical reactions within the cell. The **cell voltage** or **electromotive force (EMF)** for the external current derived from a cell is the difference in the standard electrode potentials of the two half cell reactions under standard conditions. But real voltaic cells will typically differ from the standard conditions. The **Nernst equation** relates the actual voltage of a chemical cell to the standard electrode potentials taking into account the temperature and the concentrations of the reactants and products. The EMF of the cell will decrease as the concentration of the active chemicals diminishes as they are used up until one of the chemicals is completely exhausted.

The theoretical energy available from the cell can be calculated using **Gibbs free energy equation** for the initial and final equilibrium states.

Fortunately such intimate knowledge of cell chemistry and thermodynamics is not usually required by the battery applications engineer.

Primary cells

In primary cells this electrochemical reaction is not reversible. During discharging the chemical compounds are permanently changed and electrical energy is released until the original compounds are completely exhausted. Thus the cells can be used only once.

Secondary cells

In secondary cells this elecrochemical reaction is reversible and the original chemical compounds can be reconstituted by the application of an electrical potential between the electrodes injecting energy into the cell. Such cells can be discharged and recharged many times.

Rechargeable Battery Action (Much Simplified)

The Charging Process

The charger strips electrons from the cathode leaving it with a net positive charge and forces them onto the anode giving it a negative charge. The energy pumped into the cell transforms the active chemicals back to their original state.

Choice of Active Chemicals

The voltage and current generated by a galvanic cell is directly related to the types of materials used in the electrodes and electrolyte.

The propensity of an individual metal or metal compound to gain or lose electrons in relation to another material is known as its electrode potential. Thus the strengths of oxidizing and reducing agents are indicated by their standard electrode potentials. Compounds with a positive electrode potential are used for anodes and those with a negative electrode potential for cathodes. The larger the difference between the electrode potentials of the anode and cathode, the greater the EMF of the cell and the greater the amount of energy that can be produced by the cell.

Electrochemical Series is a list or table of metallic elements or ions arranged according to their electrode potentials. The order shows the tendency of one metal to reduce the ions of any other metal below it in the series.

A sample from the table of standard potentials shows the extremes of the table.

Strengths of Oxidizing and Reducing Agents

Cathode (Reduction) Half-Reaction	Standard Potential E ° (volts)
Li + (aq) + e - -> Li(s)	-3.04
K + (aq) + e - -> K(s)	-2.92
Ca 2+ (aq) + 2e - -> Ca(s)	-2.76
Na + (aq) + e - -> Na(s)	-2.71
Zn 2+ (aq) + 2e - -> Zn(s)	-0.76
Cu 2+ (aq) + 2e - -> Cu(s)	0.34
O 3 (g) + 2H + (aq) + 2e - -> O 2 (g) + H 2 O(l)	2.07
F 2 (g) + 2e - -> 2F - (aq)	2.87

The values for the table entries are reduction potentials, so lithium at the top of the list has the most negative number, indicating that it is the strongest reducing agent. The strongest oxidizing agent is fluorine with the largest positive number for standard electrode potential.

The table below shows some common chemicals used for battery electrodes arranged in order of their relative electrode potentials.

Anode Materials (Negative Terminals)	**Cathode Materials** (Positive Terminals)
BEST - Most Negative	BEST Most Positive
Lithium	Ferrate
Magnesium	Iron Oxide
Aluminium	Cuprous Oxide
Zinc	Iodate
Chromium	Cupric Oxide
Iron	Mercuric Oxide
Nickel	Cobaltic Oxide
Tin	Manganese Dioxide
Lead	Lead Dioxide
Hydrogen	Silver Oxide
Copper	Oxygen
Silver	Nickel Oxyhydroxide
Palladium	Nickel Dioxide

Mercury	Silver Peroxide
Platinum	Permanganate
Gold	Bromate
WORST Least Negative	WORST Least Positive

Cells using aqueous (containing water) electrolytes are limited in voltage to less than 2 Volts because the oxygen and hydrogen in water dissociate in the presence of voltages above this voltage. Lithium batteries (see below) which use non-aqueous electrolytes do not have this problem and are available in voltages between 2.7 and 3.7 Volts. However the use of non-aqueous electrolytes results in those cells having a relatively high internal impedance.

Alternative chemical reactions

More recently new cell chemistries have been developed using alternative chemical reactions to the traditional redox scheme.

Metal Hydride Cells

Metal hydride cell chemistry depends on the ability of some metals to absorb large quantities of hydrogen. These metallic alloys, termed hydrides, can provide a storage sink of hydrogen that can reversibly react in battery cell chemistry. Such metals or alloys are used for the negative electrodes.The positive electrode is Nickel hydroxide as in NiCad batteries. The electrolyte, which is also a hydrogen absorbent aqueous solution such as potassium hydroxide, takes no part in the reaction but serves to transport the hydrogen between the electrodes.

Lithium Ion Cells

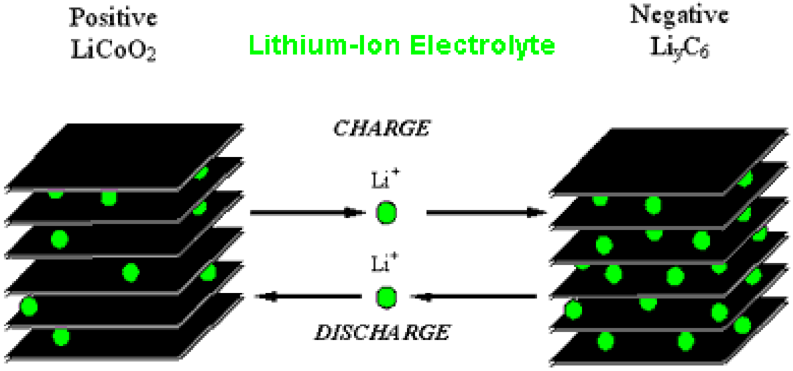
Rather than the traditional redox galvanic action, Lithium ion secondary cell chemistry depends on an "intercalation" mechanism . This involves the insertion of lithium ions into the crystalline lattice of the host electrode without changing its crystal structure. These electrodes have two key properties

1. Open crystal structures which allow the the insertion or extraction of lithium ions
2. The ability to accept compensating electrons at the same time

Such electrodes are called intercalation hosts.

In a typical Lithium cell, the anode or negative electrode is based on Carbon and the cathode or positive electrode is made from Lithium Cobalt Dioxide or Lithium Manganese Dioxide. (Other chemistries are also possible)

Since Lithium reacts violently with water, the electrolyte is composed of non aqueous organic Lithium salts and acts purely as a conducting medium and does not take part in the chemical action, and since no water is involved in the chemical action, the evolution of hydrogen and oxygen gases, as in many other batteries, is also eliminated.

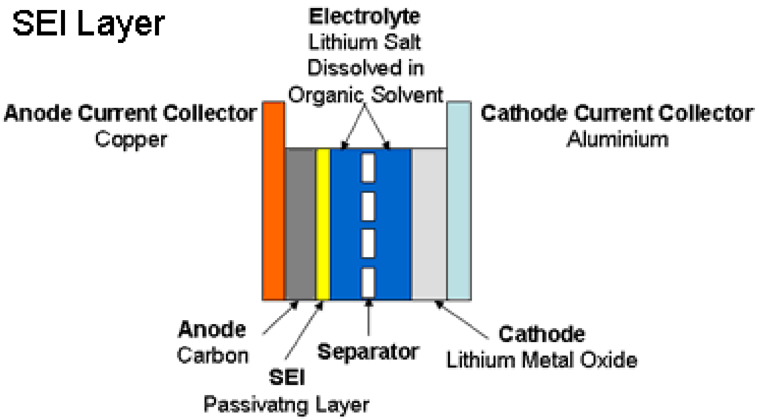


During discharge Lithium ions are dissociated from the anode and migrate across the electrolyte and are inserted into the crystal structure of the host compound. At the same time the compensating electrons travel in the external circuit and are accepted by the host to balance the reaction. The process is completely reversible. Thus the Lithium ions pass back and forth between the electrodes during charging and discharging. This has given rise to the names "Rocking chair", "Swing" or "Shuttlecock" cells for the Lithium ion batteries.

- **Solid Electrolyte Interface/Interphase (SEI)**

  The SEI layer is essential for the stability of Lithium secondary cells using carbon anodes

The electrolyte reacts vigorously with the carbon anode during the initial formation charge and a thin passivating SEI layer builds up moderating the charge rate and restricting current



The deposition of the SEI layer is an essential part of the formation process when the cells take their first charge.

BUT the SEI layer increases the cell internal impedance and reduces the possible charge rates as well as the high and low temperature performance.

Excessive heat can cause the protective SEI barrier layer to beak down allowing the anode reaction to restart releasing more heat leading to thermal runaway.

The thickness of the SEI layer increases with age reducing cell capacity and hence cycle life.

Lithium Titanate Oxide (LTO) anodes do not react adversely with the commonly used electrolytes in Lithium Ion cells hence no SEI layer is formed nor is it needed in LTO cells. This allows new degrees of freedom in mofifying cell performance. See **Lithium Cell Variants**

Variations on the Lithium technology are also used in primary cells which were originally developed for space and military applications. These include Lithium-thionyl chloride and Lithium-sulphur dioxide chemistries which use reactive electrolytes and liquid cathodes to obtain higher energy and power densities.

Alternative chemistries - Special flavours

Designing a better battery is not simply a matter of choosing a pair of elements with a larger difference in electrode potentials, there are many other factors which come into play. These may be: availability and cost of the raw materials, stability or safety of the chemical mix, manufacturability of the components, reversibility of the electrochemical reaction, conductivity of the components, operating temperature range and quite possibly the desire to circumvent some other manufacturer's patent. All of these considerations lead to the use a limited range of basic chemistries but with a wider variety of proprietary material formulations.

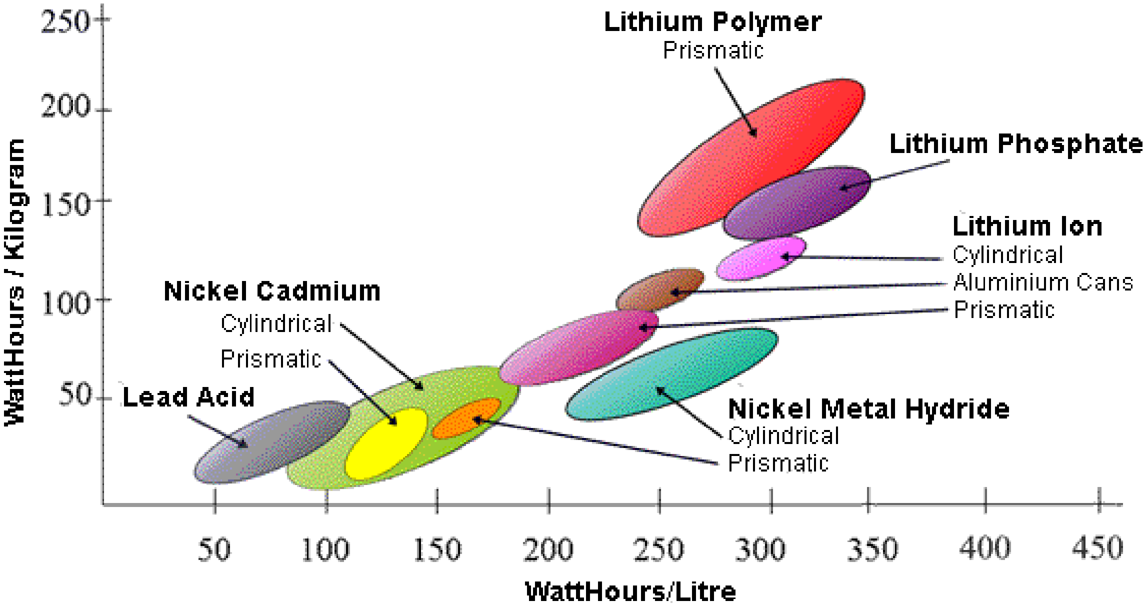
Over the years a wide range of cell chemistries and additives has been developed to optimise cell performance for different applications. Alternative active compounds may be substituted to increase energy densities (See below), increase the current capacity, reduce internal impedance, reduce the self discharge, increase the terminal voltage, improve the coulombic efficiency or reduce costs.
Additional compounds may be incorporated to modify the behaviour of the active compounds to increase cycle life, to prevent corrosion or leakage, to control polarisation or to increase safety. These could include catalysts which may be used to promote or accelerate desired chemical actions such as recombination of the active chemicals in sealed cells. They could also include inhibitors which may be added to slow down or prevent unwanted physical or chemical actions such as the formation of dendrites.

Added to the range of available cell chemistries are the different cell capacities and physical constructions of the cells, the battery applications engineer thus has a wide variety of options from which to choose.

Energy Density

The energy density is a measure of the amount of energy per unit weight or per unit volume which can be stored in a battery. Thus for a given weight or volume a higher energy density cell chemistry will store more energy or alternatively for a given storage capacity a higher energy density cell will be smaller and lighter. The chart below shows some typical examples.

Relative Energy Density of Some Common Secondary Cell Chemistries



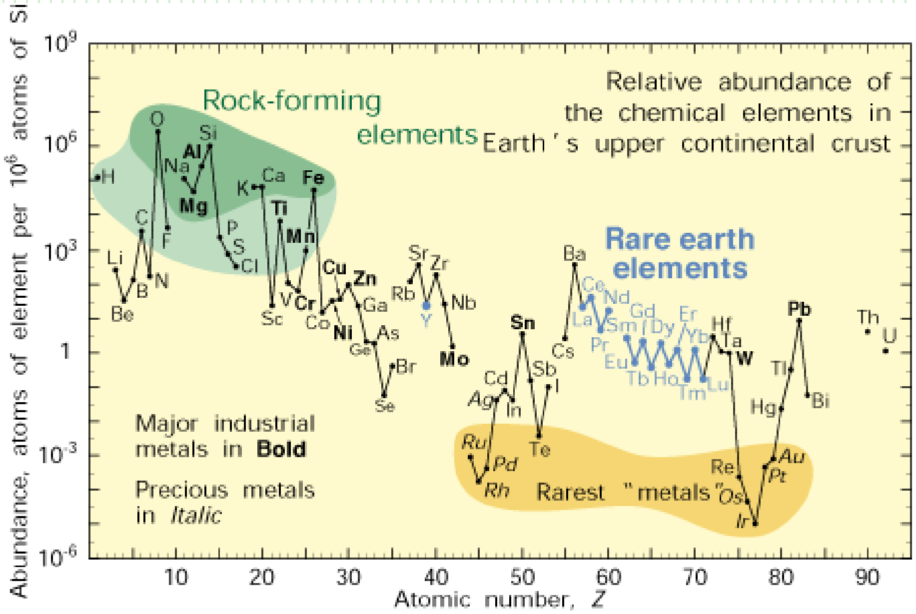
In general higher energy densities are obtained by using more reactive chemicals. The downside is that more reactive chemicals tend to be unstable and may require special safety precautions. The energy density is also dependent on the quality of the active materials used in cell construction with impurities limiting the cell capacities which can be achieved. This is why cells from different manufacturers with similar cell chemistries and similar construction may have a different energy content and discharge performance.

Note that there is often a difference between cylindrical and prismatic cells. This is because the quoted energy density does not usually refer to the chemicals alone but to the whole cell, taking into account the cell casing materials and the connections. Energy density is thus influenced or limited by the practicalities of cell construction.

Supply of the Basic Chemical Elements

Worried about the availability of exotic chemicals and the effect future demand may have on prices?

The chart below shows the relative abundance of chemical elements in the earth's crust.



Source - U.S. Geological Survey Fact Sheet 087-02

Note - From the chart above Lithium is between 20 and 100 times more abundant in terms of the number of atoms than Lead and Nickel. The reason it is less common is that Lithium, being much more reactive than either metal, is not usually found in its free state, but is combined with other elements. By contrast Lead being less reactive is more often found in its free state and is easier to extract and purify. The heavy metals Cadmium and Mercury whose use is now deprecated because of their toxicity are 1000 times less common than Lithium.

Lithium Consumption in EV and HEV Batteries

The Lithium content in a high capacity Lithium battery is actually quite small.

Taking a Lithium Cobalt cell as an example, the Lithium content in the $LiCoO_2$ cathode material is only 7% by weight. The cathode material itself makes up between 25% and 33% of the battery weight so that the Lithium content of the electrode in the cell amounts to about 2% of the weight cell. In addition the electrolyte which accounts for about 10% of the battery weight also contains smaller amounts of dissolved Lithium so that the total Lithium content in a high energy battery is typically less than 3% by weight.

Lithium batteries used in EVs and HEVs weigh about 7 Kg per KWh and so that the Lithium content will be about 0.2 Kg per kWh. A typical EV passenger vehicle may use batteries with capacities between 30KWh and 50KWh so that the Lithium content will be about 6 Kg to 10 Kg per EV battery.

The capacity of HEV batteries is typically less than 10% of the capacity of an EV battery and the weight of Lithium used is correspondingly 10% less.

Thus 1 million EVs would consume less than 10,000 tons of Lithium (without recycling) and 1 million HEVs would consume no more than 1,000 tons

Considering the availabile supply of Lithium (see next section) there is more than enough Lithium available to satisfy the world demand for high energy automotive batteries.

Lithium Supplies

Lithium is the 31st most abundant element in the Earth's crust with an abundance of 20 ppm. This compares with Lead (14 ppm), Tin (2.3 ppm), Cobalt (25 ppm) and Nickel (84 ppm). It is found in small amounts in nearly all igneous rocks and mineral springs with particularly large deposits in China, North America, Brazil, Chile, Argentina, USSR, Spain, and parts of Africa.

The current estimate of exploitable reserves (apart from recovery from seawater) is estimated as 28.4 million tons. In addition the earth's 1.4×10^{21} kilograms of seawater contain a relatively high 0.17 ppm of Lithium which means that there are over 200 billion tons of Lithium in the world's oceans.

The US Geological Survey reported the world production of Lithium in 2006 was 333,000 metric tons, slightly down on the previous year. China is expected to bring on production of 45,000 tons of Lithium per year from brine based facilities in 2010

Toxicity of Lithium

In case you wondered whether there were any toxic effects associated with Lithium, it is claimed that Lithium on the contrary has therapeutic benefits. The soft drink "7Up" started life in 1929, two months before the Wall Street Crash, with the catchy name "Bib Label Lithiated Lemon-Lime Soda". "7Up" contained Lithium Citrate until 1950 when it was reformulated, some say because of Lithium's association with mental illness. Since the 1940s, Lithium in the form of Lithium Carbonate has been used successfully in the treatment of mental disorder particularly manic depression. As with most chemicals however, small doses may be safe or therapeutic, but too much can be fatal.

Make your own battery at home or at school

See Homebrew Batteries for instructions on how to make a battery using simple materials available at home.

Battery Constuction

Information about the mechanical design of batteries can be found on the following pages:

- Cell Construction
- Battery Pack Design

Practical Cell Chemistries

Some of the most common cell chemistries are described and the applications for which they are suitable if you follow the links below:-

Primary Cells

- Leclanché Cells
- Alkaline Cells
- Silver Oxide Cells
- Zinc Air Cells
- Lithium Primary Cells
- Water Activated Batteries
- Thermal Batteries

Secondary Cells

- Lead Acid
- Nickel Iron
- Nickel Cadmium
- Nickel Metal Hydride
- Nickel Zinc
- Nickel Hydrogen
- Lithium Secondary Cells
- Sodium Sulphur
- Flow Cells (Redox)
- Zebra Cells
- Other Galvanic Cells

Unusual Batteries

- Urine Battery - No its not a joke
- Ampoule Batteries
- Thin Film Batteries
- Homebrew Battery

Cell chemistry Comparison Chart

Alternative Energy Generation and Storage Methods

- Capacitors and Supercapacitors
- Fuel Cells

- Solar Cells
- Non-Chemical Energy Storage Methods

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Frequently Asked Questions

About Us. What we do and what we don't do.

1) Who is Woodbank Communications?

2) Can you supply a battery (or charger) for my application?

3) Can you provide technical advice to solve a problem I have with my battery application?

4) Can you please provide more details or explanations of topics on the Web site?

5) Can you please help me my homework / hobby / research project?

6) How can I make a contribution (information - not money) to your Web site?

7) Can you please exchange links with my Web site?

8) Why do the Electropaedia pages appear on the mpoweruk.com domain?

Answers

1) Who is Woodbank Communications?

Woodbank Communications Ltd. is a consultancy company providing training on Batteries and Battery Management Sytems for electric traction, and high capacity energy storage applications.

2) Can you supply a battery (or charger) for my application?

No. We don't supply batteries or chargers. However we do have extensive contacts in the battery manufacturing business and if you have a high volume requirement for a custom design we can pass on your request to a suitable battery or charger manufacturer.

If you wish to take advantage of this offer, please note that it applies to custom batteries and their associated chargers only and that suppliers will expect conditions, such as the following, to apply:

- Most suppliers will levy non recurring engineering (NRE) development and tooling costs which could be between £100,000 and £250,000 or more for an automotive (EV) battery, depending on the complexity of the project. See **Battery Pack Costs**
- The pre-production samples (the first five or more units) will probablly cost about double the cost of volume production units.
- Suppliers will most likely not take on the development unless it is accompanied by a firm commitment to follow through with a volume manufacturing contract.

It you are prepared to accept these conditions, go to our **Quotation Page** to let us know your requirements. There is no charge for this service.

Please note that this service for high volume custom batteries and chargers only. We do not have the resources to procure or sell standard batteries, replacement batteries, batteries for low volume projects or their associated chargers.

3) Can you provide technical advice to solve a problem I have with my battery application?

We try to provide as much helpful information as possible on this web site but we do not have the resources to answer enquiries about individual technical problems on a free of charge basis nor do we solicit such business. Our business is providing technical training on batteries and battery applications for which we charge a fee. If you wish to take advantage of this service please email us at **Woodbank Communications**

4) Can you please provide more details or explanations of topics on the Web site?

and

5) Can you please help me my homework / hobby / research project?

The information provided by Woodbank Communications is given freely but limited to what is published here on the Web site. So please don't ask for more details, explanations or technical advice, nor for help with homework, hobby or research projects. Hopefully you will find what you want here on the site.

6) How can I make a contribution to your Web site?

Thank you for your offer. If you have some interesting information to contribute to the site, please use the **Feedback Form** for this purpose.

7) Can you please exchange links with my Web site?

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8) Why do the Electropaedia pages appear on the mpoweruk.com domain?

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How To Specify Batteries

The battery industry has provided us with an enormous range of battery sizes , shapes, voltages, capacities and chemistries. With so many to choose from, how does the applications engineer select the optimum battery for the intended application? This section outlines the information needed to specify a battery.

Don't leave it too late. To avoid problems of last minute changes to the system power budget, or in finding a battery to fit the available space left in the product casing, the requirements for the power source should be considered as early as possible in the design cycle.

The section on Performance Characteristics describes how cells perform in practice. The section on Battery Pack Design describes some of the many possible battery pack functions and designs. A summary of the most commonly available cell technologies is given on the "Cell Chemistries" page with links to pages describing the advantages and disadvantages of each type.

Most of the information needed to specify a battery for a particular application is listed on the "Request for Quotation" page and in the main this should be self explanatory. Some further explanation is however given below.

Trade offs

The starting point is the application and its power consumption requirements. For many consumer applications, the design trade offs are between cost and weight or volume and cycle life which can equally well be satisfied by a wide range of low power, low capacity batteries based on a range of cell chemistries. Convenience is also an issue.

Customers for higher power applications and industrial users will more likely compare batteries on the cost of ownership taking into account the capital cost, the running costs and the battery cycle life. These industrial applications may require batteries working at the limits of the technology. In this case the trade off may be between power output and storage capacity. Knowledge of the application priorities is an important factor in determining the technology to be used.

Performance Requirements

Details and explanations of cell behaviours are given in the section on Performance Characteristics. The applications engineer must match the cell performance to the requirements of the application.

Requirement for Recharging?

The pros and cons of using rechargeable cells for the application are discussed in separate sections on Primary Cells and Secondary Cells .

Electrical Specification

The working voltages and currents required by the application are obviously needed for specifying the battery, not just the nominal, but also the maxima and minima.

Beware of cell manufacturers' published specifications. They are not deliberately misleading but they may need some interpretation. You may find the quoted Amphour capacity of a cell based on a prolonged discharge of 10 hours or more rather than the 1 hour at the C rate which is used for most low power batteries. (The SAE uses 20 hours as standard). This does not give a true indication of the capacity available if the cell were to be discharged at the C rate which could be as low as half the 20 hour capacity. On the other hand the cell capacity may be quoted at the C rate but the cell may be designed for low discharge rates only and may not be able to sustain a prolonged continuous discharge at the C rate.

Voltage Requirements

The battery should be dimensioned to be able to support the full operating voltage range of all the devices in the application. There is no point however in specifying a battery operating voltage range which is greater than the operating voltage limits of the application for which the battery is intended. The battery will deliver excessive currents when it is fully charged or, if the application has a protection circuit, it will prevent the application from starting. At the other end of the discharge curve, when the application cuts off at its lower limit, the battery becomes unusable when there is still a substantial amount of energy left in the cells. The battery operating voltage range should therefore be less than the operating voltage range of the circuit it is designed to power.

Note also that the battery terminal voltage decreases towards the end of the discharge cycle and this should be taken into account when specifying the battery voltage. Similarly, at lower temperatures the battery internal impedance may increase resulting in a lower terminal voltage available to the application.

Multiple Voltages

Many designs require multiple supply voltages because of the range of active devices used in the application. In such cases it is not necessary to have multiple batteries. The various voltages can be derived from a single power supply rail using DC/DC converters, charge pumps and buck and boost and LDO and switch mode regulators singly or in combination. A wide range of power management integrated circuits is available for this purpose.

Current Requirements

The average and the pulsed current drains required by the application are key factors in determining the battery capacity and for specifying the associated protection circuits.

One factor often overlooked is the start-up or surge current. When equipment is first switched on, extremely high currents may flow for a very short time until the circuit reaches its steady state condition. This could be due to capacitors charging up or other effects. This is a particular problem for circuits powering electric motors. The current through the motor is controlled by the difference between the battery voltage and the motor's generated voltage (otherwise called the back EMF). When the motor is first connected up to the battery (with no motor speed controller) there is no back EMF. So the current is controlled only by the battery voltage, motor resistance (and inductance) and the battery leads. Without any back emf before the motor starts to turn, it therefore draws a very large large surge current. It may be necessary to program a delay into fast acting protection circuits to avoid false triggering during start-up. Alternatively it may be possible to minimise the problem by applying the load progressively rather than instantaneously.

Similarly batteries used in UPS applications often experience a dramatic initial voltage drop when called upon This is known as a "coup de fouet" or "whiplash." The voltage recovers after a short time once the electro-chemical discharge process is stabilised and protection circuits should specified accordingly.

Limiting the quiescent current when the system is powered down is also an important consideration particularly if primary cells are used.

Capacity

The battery capacity required is determined by the usage profile of the application and the desired time between charges (or battery replacement in the case of primary batteries). In general it is the average current in amps multiplied by the time between charges. The battery pack should not be designed in isolation from the charger. Using inappropriate chargers can seriously shorten the cycle life of the battery and may even be dangerous. The pack designer needs to interface with the charger designer to ensure that the correct charger is specified for the chosen cell chemistry. See also the section on Chargers and the Charger Specification Checklist.

Duty Cycle

It is important to understand the pattern of current usage in order to calculate the overall current drain on the battery. The table below shows typical usage of portable telecommunications equipment.

	Standby Mode	Receive Mode	Transmit Mode
Percent	80%	10%	10%
Minutes per hour	48	6	6
Current drain during mode	10 mA	62 mA	325 mA

Average current for mode	8 mA	6.2 mA	32.5 mA

More complex applications such as electric vehicles have a much more variable load pattern depending on driving conditions. An example is given in the section on Battery Testing. These simulated load predictions are an essential tool for dimensioning a new automotive battery systems.

The battery must be able to handle the peaks as well as the average load.

Timing Issues

Specifying the usage profile of the battery is particularly important for high power applications.

Standby and emergency power applications impose particular timing requirements on the battery. Depending on the application, the battery may be required to react to a power outage within milliseconds or seconds to avoid loss of data, process interruption or other system failures. Such events don't occur very often but when they do the battery may be required to provide power for very short periods, just long enough for the system to achieve a graceful shut down, or long enough for a standby generator to fire up. In these cases where the battery is expected to take over from an AC mains source, it must be supported by a fast acting electronic inverter to convert the DC battery output to the required clean AC voltage and frequency. The battery should therefore be specified in conjunction with the associated inverter. See also AC Batteries.

Depth of Discharge

In load levelling applications, batteries are required to provide power when the prime power source is not available or uncontrolled and intermittent. Examples are solar and wind powered applications. In these applications the battery will be required to provide power for prolonged periods on a daily basis. The battery is thus subject to deep discharges and many charge - discharge cycles. Special battery constructions are needed to meet these very onerous loading conditions. For these applications it is important to specify the expected Depth of Discharge which the battery must support as well as the Duty Cycle.

Similar requirements apply to electric and hybrid vehicle applications.

Self Discharge

All batteries progressively lose their charge over time, some much more quickly than others, even if they are not used. It is important to be aware of the time finished batteries may be in the consumer supply pipeline, often called the shelf life, after they leave the factory. This is particularly true with primary cells, to ensure they still have a reasonable remaining lifetime when they are eventually sold. Problems can be avoided by minimising the time the batteries will be in the supply pipeline (including shipping times and times in the manufacturers', assemblers', wholesalers' and retailers' inventories) or by choosing cells with a low self discharge rate.

Secondary batteries usually have a higher self discharge rate but at least they can be recharged. For rechargeable batteries the self discharge rate affects the time between charges and this could influence the choice of cell chemistry. Some examples of typical self discharge rates are given on the section on Performance Characteristics.

Environmental Conditions

Batteries have a limited temperature range over which they work. Attempting to use the battery outside these limits will usually result in a permanent degradation in performance or complete failure. The specification should therefore stipulate these limits. Note that the actual working temperature of the battery will not be the ambient temperature but some higher temperature depending on the heat generated by the battery application and the heat removed from the battery by conduction and radiation. See Thermal Management.

If the product operating temperature requirements exceed the battery operating limits it will be necessary to incorporate heating or cooling into the pack as appropriate.

Dimensions, Weight and Construction

The pack designer also needs to know the dimensions of the battery or the cavity destined to contain it along with the location and specification of the connectors and the packaging requirements for interfacing with the intended product.

The allowable weight can also be a deciding factor when choosing a cell. For a given capacity there is roughly a 4:1 ratio in the range weights of available cells with different technologies.

Safety Requirements

The battery pack should be intrinsically safe whether attached to, or separate from, the product in which it is used and so should include at least the necessary protection circuits. The battery will normally be designed to meet all international safety standards, but the application may have particular monitoring and control requirements that must be specified before work can commence on the pack design. See more in the section on Battery Safety.

International Standards

The design, manufacturing, use and disposal of batteries, as with many electrical products, are subject to a wide variety of standards and regulations imposed by national and international regulatory organisations mainly to protect the user and the environment. The pack designer needs to be aware of the applicable regulations in the markets in which the product will be sold and must ensure that the pack design is fully compliant with these requirements. A list of major standards setting organisations and typical standards is given in the section on International Standards.

Costs

The target cost of the battery is obviously an important part of the specification. The unit cost of the battery is dependent on the battery chemistry employed, however a high cost chemistry may offer a longer cycle life. One way of comparing different options is to use the cost per cycle as the basis of comparison, another is the cost per Watthour of delivered energy. For consumer products these may not be the ways the product is judged by the end user unless some attempt is made to explain the benefits of an alternative technology. More likely the battery will judged by its contribution to the initial product (capital) cost.

When comparing the cost of battery power with other sources of power it may be necessary to take into account net present values and cash flows as well as lifetime costing. For example, the capital cost of a lithium traction battery with its associated electric drive may be very high compared with the cost of a petrol or diesel engine but the running costs of the battery will be much lower since the electricity costs less than the fuel. Based on capital costs the battery solution is not attractive. But when purchasing a new vehicle the user does not purchase all of the fuel at the same time. It is purchased over the lifetime of the vehicle. If batteries were leased, a more reasonable comparison of initial costs and running costs could be made.

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State of Charge (SOC) Determination

Knowing the amount of energy left in a battery compared with the energy it had when it was full gives the user an indication of how much longer a battery will continue to perform before it needs recharging. Using the analogy of a fuel tank in a car, State of Charge (SOC) estimation is often called the "Gas Gauge" or "Fuel Gauge" function.

The SOC is defined as the available capacity expressed as a percentage of some reference, sometimes its rated capacity but more likely its current (i.e. at the latest charge-discharge cycle) capacity but this ambiguity can lead to confusion and errors. It is not usually an absolute measure in Coulombs, kWh or Ah of the energy left in the battery which would be less confusing.

The preferred SOC reference should be the rated capacity of a new cell rather than the current capacity of the cell. This is because the cell capacity gradually reduces as the cell ages. For example, towards the end of the cell's life its actual capacity will be approaching only 80% of its rated capacity and in this case, even if the cell were fully charged, its SOC would only be 80% of its rated capacity. Temperature and discharge rate effects reduce the effective capacity even further. This difference in reference points is important if the user is depending on the SOC estimation as he would in a real gas gauge application in a car.

Unfortunately the SOC measurement reference is often defined as the current capacity of the cell instead of the rated capacity. In this case a fully charged cell, nearing the end of its life, could have an SOC of 100% but it would only have an effective capacity of 80% of its rated capacity and adjustment factors would have to be applied to the estimated capacity to compare it to its rated new capacity. Using the current capacity rather than the rated capacity is usually a design shorcut or compromise to avoid the complexity of determining and allowing for the age related capacity adjustments which are conveniently ignored.

Basing the SOC estimate on the current capacity of the battery rather than its rated capacity when new is equivalent to progressively reducing the capacity of the fuel tank over the lifetime of the vehicle without informing the driver. If an accurate estimate of the charge remaining in the battery is required the ageing and environmental factors must be taken into account.

For cell balancing applications, it is only necessary to know the SOC of any cell relative to the other cells in the battery chain. Since all the cells will have been subject to the same influences during their lifetime, the ageing and environmental adjustments, which apply equally to all cells, can be ignored for this purpose.

SOC Accuracy Requirements

A knowedge of the SOC is particularly important for large Lithium batteries. Of all the common cell chemistries Lithium is the most chemically reactive and the only one which needs electronic battery management systems (BMS) to keep the battery within a safe operating window and to ensure a long cycle life. Control of the SOC is a major function of the BMS. Furthermore, automotive applications, one of the main uses of large Lithium batteries, need very precise control of the SOC for efficient and safe management of the energy flows.

- In **EV applications** the SOC is used to determine range. It should be an absolute value based on capacity of the battery when new, not a percentage of current capacity which could result in an error of 20% or more due to battery ageing.
  Automotive fuel guages are notoriously imprecise so an SOC accuracy of 5%, if it could be achieved, would probably be satisfactory for such applications.
- In **HEV applications** the SOC determines when the engine is switched on and off. SOC errors over 5% could seriously affect the system fuel efficiency. An accuracy significantly better than 5% is therefore desirable.

See Estimation Accuracy possibilities below

Methods of Determining the State of Charge

Several methods of estimating the state of charge of a battery have been used. Some are specific to particular cell chemistries. Most depend on measuring some convenient parameter which varies with the state of charge.

Direct Measurement

This would be easy if the battery could be discharged at a constant rate. The charge in a battery is equal to the current multiplied by the time for which it flowed. Unfortunately there are two problems with this. In all practical batteries, the discharge current is not constant but diminishes as the battery becomes discharged, usually in a non-linear way. Any measurement device must therefore be able to integrate current over time. Secondly, this method depends on discharging the battery to know how much charge it contained. In most applications except perhaps in qualification testing, the user (or the system) needs to know how much charge is in the cell without discharging it.

It is not possible either to measure directly the effective charge in a battery by monitoring the actual charge put into it during charging. This is because of the Coulombic efficiency of the battery. Losses in the battery during the charge - discharge cycle mean that the battery will deliver less charge during discharge than was put into it during charging.
The Coulombic efficiency or charge acceptance is a measure of how much usable energy is available during discharging compared with the energy used to charge the cell. Charge efficiency is also affected by temperature and SOC.

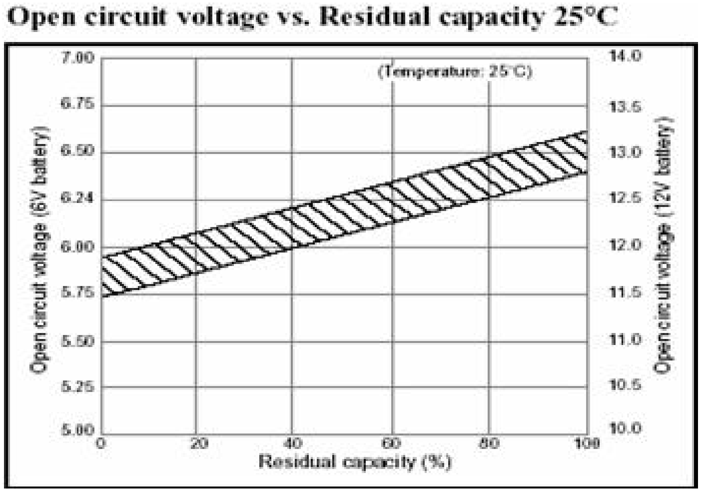
SOC from Specific Gravity (SG) Measurements

This is the customary way of determining the charge condition of lead acid batteries. It depends on measuring changes in the weight of the active chemicals. As the battery discharges the active electrolyte, sulphuric acid, is consumed and the concentration of the sulphuric acid in water is reduced. This in turn reduces the specific gravity of the solution in direct proportion to the state of charge. The actual SG of the electrolyte can therefore be used as an indication of the state of charge of the battery. SG measurements have traditionally been made using a suction type hydrometer which is slow and inconvenient.

Nowadays electronic sensors which provide a digital measurement of the SG of the electrolyte can be incorporated directly into the cells to give a continuous reading of the battery condition. This technique of determining the SOC is not normally suitable for other cell chemistries.

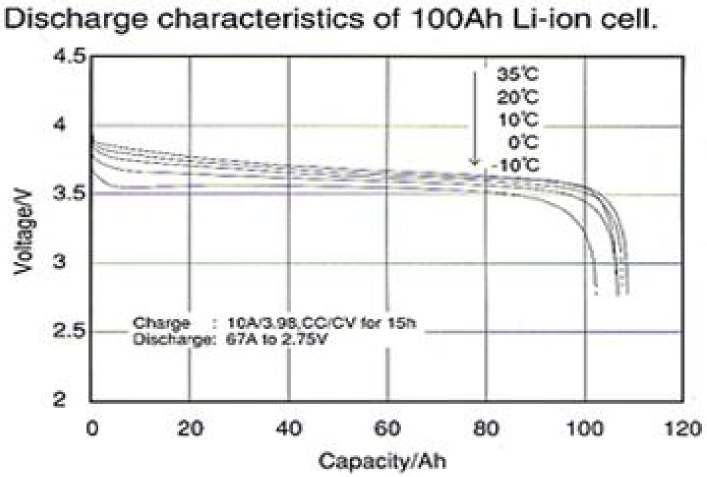
Voltage Based SOC Estimation

This uses the voltage of the battery cell as the basis for calculating SOC or the remaining capacity. Results can vary widely depending on actual voltage level, temperature, discharge rate and the age of the cell and compensation for these factors must be provided to achieve a reasonable accuracy. The following graph shows the relationship between the Open Circuit Voltage and the Remaining Capacity at constant temperature and discharge rate for a high capacity Lead Acid cell. Note that the cell voltage diminishes in direct proportion to the remaining capacity.



Lead Acid Battery

Problems can occur with some cell chemistries however, particularly Lithium which exhibits only a very small change in voltage over most of the charge/discharge cycle. The following graph shows the discharge curve for a high capacity Lithium-ion cell. This is ideal for the battery application in that the cell voltage does not fall appreciably as the cell is discharged, but for the same reason, the actual cell voltage is not a good measure of the SOC of the cell.



The rapid fall in cell voltage at the end of the cycle could be used as an indication of imminent, complete discharge of the battery, but for many applications an earlier warning is required. Fully discharging Lithium cells will dramatically shorten the cycle life and most applications will impose a limit on the DOD to which the cell is submitted in order to prolong the cycle life. While the cell voltage can be used to determine the desired cut off point, a more accurate measure is preferred for critical applications.

Current Based SOC Estimation - (Coulomb Counting)

The energy contained in an electric charge is measured in Coulombs and is equal to the integral over time of the current which delivered the charge. The remaining capacity in a cell can be calculated by measuring the current entering (charging) or leaving (discharging) the cells and integrating (accumulating) this over time . In other words the charge transferred in or out of the cell is obtained by accumulating the current drain over time. The calibration reference point is a fully charged cell, not an empty cell, and the SOC is obtained by subracting the net charge flow from the charge in a fully charged cell. This method, known as Coulomb counting, provides higher accuracy than most other SOC measurements since it measures the charge flow directly. However it still needs compensation to allow for the operating conditions as with the voltage based method.

Three current sensing methods may be used.

- Current Shunt The simplest method of determining the current is by measuring the voltage drop across a low ohmic value, high precision, series, sense resistor between the battery and the load known as a current shunt. This method of measuring current causes a slight power loss in the current path and also heats up the battery and is inaccurate for low currents.
- Hall effect transducers avoid this problem but they are more expensive. Unfortunately they can not tolerate high currents and are susceptible to noise.
- GMR magnetoresistive sensors are even more expensive but they have higher sensitivity and provide a higher signal level. They also have better high temperature stability than Hall effect devices.

Coulomb counting depends on the current flowing from the battery into external circuits and does not take account of self discharge currents or the Coulombic efficiency of the battery.

Note that in some applications such as automotive batteries the "continuous" battery current is not monitored. Instead the current is sampled and the continuous current is reconstructed from the samples. In such cases the sampling rate must be fast enough to capture the current peaks and troughs associated with the acceleration and regenerative braking corresonding to the user's driving style.

Internal Impedance

During the cell charge - discharge cycles the composition of the active chemicals in the cell changes as the chemicals are converted between the charged and discharged states, and this will be reflected in changes to the cell impedance. Thus measurements of cell internal impedance can also be used to determine SOC however these are not widely used due to difficulties in measuring the impedance while the cell is active as well as difficulties in interpreting the data since the impedance is also temperature dependent.

Fuzzy Logic and other similar models have been used to overcome these problems and ASICs have been developed for this purpose.

Other State of Charge Measures

With a constant load and constant ambient conditions, Lithium cells have a linear SOC discharge characteristic over time which could possibly allow the SOC to be determined from running time, or in the case of a pure electric vehicle, distance travelled. This method depends on maintaining a constant driving pattern and major inaccuracies will be introduced if the driving pattern changes. It can also not be applied when intermittent charging is involved as with HEVs.

While the measure may not be suitable as a basis for BMS in automotive use, it could be used for simple applications such as bicycle range indicators and it could also provide a verification check of the BMS model predictions for safety purposes.

Factors Influencing the State of Charge in Lithium Batteries

Unfortunately neither voltage measurement nor coulomb counting alone is sufficient for high accuracy fuel gauging because the charge a cell is able to accept or deliver depends not just on the fundamental cell design but also on both the age of the cell and its short and long term operating environment.

Usable Capacity

SOC estimations for Lithium cells are complicated by the fact that the useable capacity of a cell is not constant but varies significantly with temperature, the charge discharge rates and with the age of the cell and lesser effect with other parameters such as the time between charges (due to the self dischage rate).

Charge - Discharge Rates

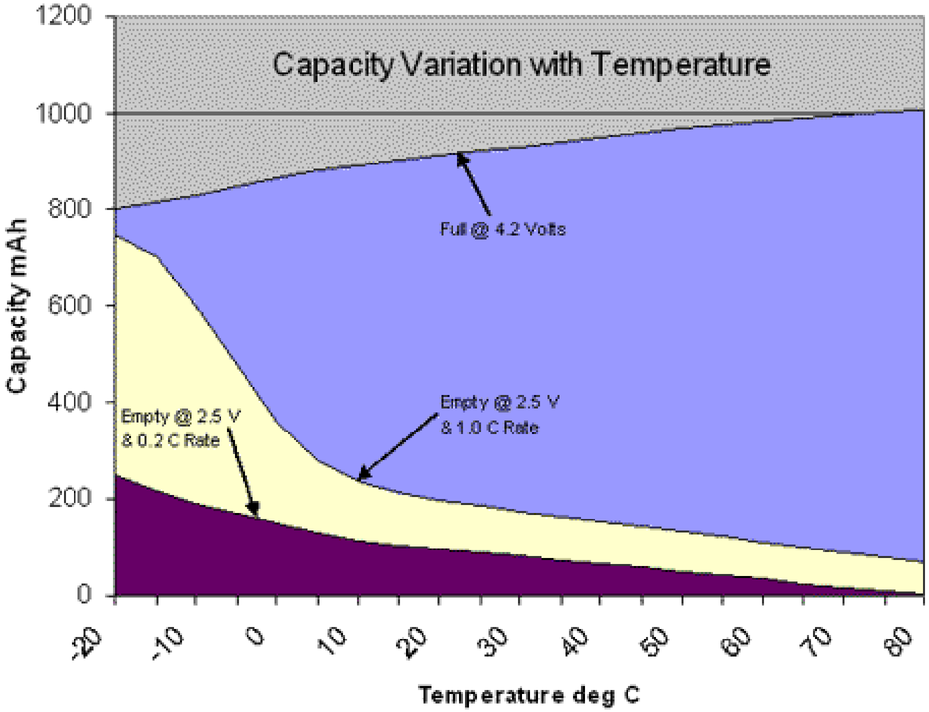
The effective capacity of a cell depends on the rate at which it is charged and discharged as illustrated in the graph on Discharge Rates. This is because the electrochemical actions in the cell take a finite time to complete and they can not follow instantaneously the electrical stimulus or load placed on the cell. This is explained in the section on Charging Times. If a cell is subject to short term charging and discharging pulses, as in EV and HEV applications, the chemical effect of a charging pulse may not be fully completed before the subsequent discharge pulse starts to reverse the process. Even with coulomb counting this can lead to errors in determining the SOC of the cell unless the rates of the chemical actions are taken into account.

Hysteresis

At the same state of charge, the open circuit voltage (OCV) following a charge is higher than the OCV following discharge. This is another manifestation of the time constant associated with the delay in the battery chemical reaction in keeping up with electrical stimulus.

Temperature and Discharge Rate

The following graph shows how the capacity of a Lithium cell varies with temperature and discharge rate. It shows that at normal working temperatures the coulombic efficiency of the cell is very high, but at low temperatures there is a major drop in efficiency particularly at high discharge rates which can give rise to serious errors in the estimation of the SOC. This phenomenon is not peculiar to Lithium cells as other cell chemistries also demonstrate a deterioration in performance at low temperatures.

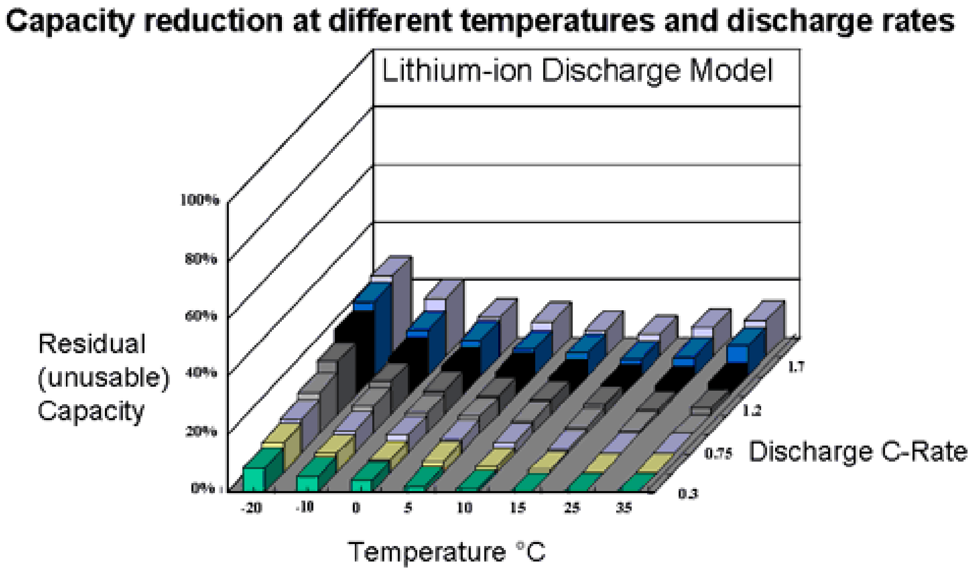


The graph shows a Lithium cell working between its specified upper and lower voltage cut -off limits of 4.2.Volts and 2.5 Volts respectively. These are considered the fully charged and the empty conditions of the cell. The "Full" line is the point at which the cell reaches full charge using the constant current - constant voltage charging method at the corresponding temperature. Two "Empty" lines are shown corresponding to two different discharge rates 0.2C and 1.0C.

The capacity of the cell at a given rate and temperature is the difference from the "Full" line and the corresponding "Empty" line.

In actual practice, the cell may be charged at one temperature and discharged at a different temperature and this must be taken into account when calculating the effective capacity of the cell. Note that the cell is very inefficient at giving up its charge at high discharge rates and low temperatures. In other words, its coulombic efficiency deteriorates dramatically at low temperatures. Note also that the cell above could be fully discharged at the high current rate yet could be further discharged at the low current rate by the number of milliamp-hours between the two "Empty" points that correspond to the present cell temperature.

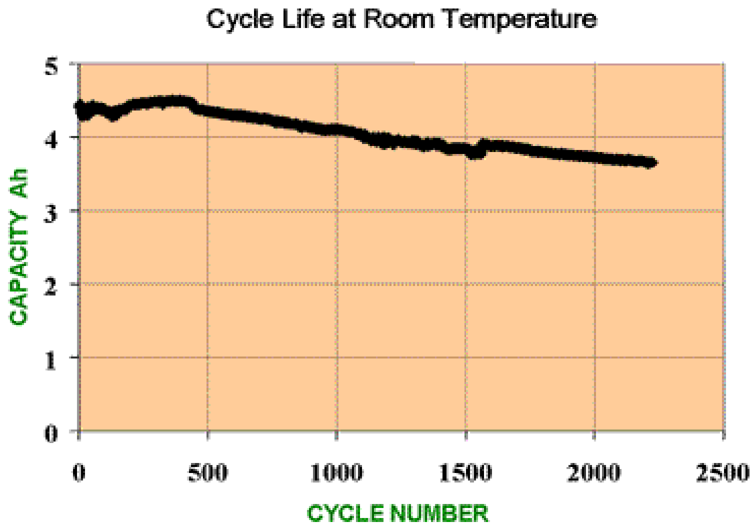
Typical cell specifications only give the capacity at 25 ºC and 0.3 C rate. The graph below shows the combined effect of rate and temperature on the effective cell capacity. Note that the available capacity is reduced at high discharge rates and though there is a slight capacity reduction when operating at high temperatures, there is a substantial reduction at low temperatures. Similar effects come into play during the charging cycle.



The above graph characterises the performance of a Lithium cell over two of its expected operating conditions. The matrix of capacity values associated with all the possible current-temperature combinations is useful as a **look up table** used by charge estimation algorithms below. This battery performance matrix is similar to an "engine map" which stores a plurality of engine performance curves under different operating conditions used in the control systems employed modern internal combustion engines.

Cell Ageing

The graph below shows how ageing affects the cell capacity. To account for this, the formulas for calculating remaining capacity must be capable of dynamically changing over time to remain accurate.



The cycle life of a cell is usually considered complete when the cell capacity has fallen to 80% of its value when the cell was new. Note that the capacity reduces in a fairly linear way as the cell ages and continues to do so after specified battery lifetime. There is no sudden death and batteries can continue to be used albeit with a reduced capacity.

Self Discharge

In addition to the charge being put into and taken out of the battery during the normal charge - discharge process, the continuing long term effect of self discharge consuming the available energy in the cell must also be taken into account.

Other Factors

Other factors such as charge/discharge efficiency also affect the cell capacity.

Calculating the SOC of Lithium Batteries

As noted above, voltage or current measurements can provide a rough indication of the SOC of a battery, but for more precision, particularly for Lithium batteries, other factors must be taken into account.

Theoretical SOC Estimation

It is possible but not necessarily practical to estimate the SOC of a battery from purely theoretical considerations. Batteries are non-linear. The SOC could be calculated from measured cell parameters and operating conditions if sufficient data were available. Unfortunately this is far too complex since there are 30 or more variables affecting cell performance some of which are much more significant than others. They are listed below for information only since this method is not used in practice (unless in a severely cut down form)'

Theoretical calculations are based on Coulomb counting modified by the cell voltage and temperature, the rate at which cells have been charged and discharged, the chemical composition of the various active chemicals and any doping which has been used, the possibility and effects of contamination, the shape and length of the physical current paths within the cell, the volume of electrolyte, the thickness of the electrolyte and the separator, the resistivity of the components, the rate of mass transfer of the ions through the electrolyte, the rate of chemical action at the surface of the electrodes or the rate of absorption of the ions into the intercalation layers, the actual surface area of the electrodes, the effective surface area of the electrodes taking into account the particle sizes of the chemicals, the effect of passivation on the electrode surface, the ambient temperature, the Joule heating effect, the self discharge rate of the cells, the time between charges plus possibly several other factors.

A theoretical calculation of the SOC will always be limited by number of effects for which equations can be developed.

Practical SOC Estimation

Alternatively the performance characteristics of a typical sample cell (or cells) can be measured and the results used as a template to represent the performance of the rest of the population. . Basing the cell performance estimates on look up tables constructed from measured data from actual cells is much simpler than carrying out theoretical estimates since it automatically takes account of most if not all the factors affecting the SOC. Look up tables are stepwise approximations of the performance response curves which represent the cell discharge performance as a function of temperature, discharge rate or other parameters. See example above. The necessary look up tables are developed from laboratory measurements under controlled conditions. The process of gathering the data and constructing the look up table is called cell characterisation and only needs to be carried out once, however a new data set or look up table must be produced for each cell chemistry variant and cell construction used.
Reusable, standard, software can be used to accommodate different data sets

Once the cells have been characterised the next step is to consider the battery application. Coulomb counting is used to provide an intial estimate of the cell SOC and this value is then modified to take account of the cell's unusable capacity corresponding to its operating point by referring to the look up table. Thus the SOC estimation is accomplished by building a model of the battery which replicates the battery characteristics in software and an algorithm which predicts its behaviour in response to various external and internal conditions.
This method of course needs sensors to provide the measurement data of the current battery status, memory to store the battery model and a microprocessor to calculate the results.

Sensors in the battery provide analogue inputs representing temperatures, cell voltages and currents to the model and precision A/D converters translate these inputs into digital form. Further information such ambient temperatures and the status of various alarms if necessary can also be provided to the model. These inputs are constantly monitored and updated at the request of the microprocessor which controls the model. The model can then use these inputs to estimate the SOC, or other, status of the battery at any instant in time.

In dynamic applications such as automotive batteries, inputs must be monitored at least once per second to ensure that no significant charge flows or critical events are missed and the SOC prediction for every individual cell in the battery must be completed during the sampling interval. Because of the complexity of the algorithm and the number of inputs involved the system must perform over a million or more floating point calculations per second. This requires a powerful microprocessor. An example of the need for continual updating of SOC estimations in a working system is given in the section on Battery Management Systems.

Estimation Accuracy of SOC Estimates Based on Look Up Tables

- **Offset Errors** (Number and Significance of influencing Factors Considered)

  For an accurate representation of the charge / discharge characteristics of the cell, similar look up tables must be developed for all the known factors which significantly affect the cell capacity (Ah) and impedance, such as cell temperature, ambient temperature, charge and discharge rates, heat dissipation rates, the cell self discharge rate charge or coulombic efficiency and the capacity degradation over the lifetime of the cell.

  If any of the key parameters which affect the usable capacity of the cell are ignored, there will be a correspondingly large offset error in the SOC estimation.

  SOC offset errors based on Coulomb counting alone, without the compensating factors, can be as high as 30%!
- **Sample Size and Validity**

  Accuracy may be limited by the small sample size used for constructing the data set and whether the samples used to characterise the cells were truly representative of the population throughout the expected production run of the cells.
- **Data Points and Prediction Algorithms**

  Accuracy will also depend directly on the number of data points in the look up table. Various algorithms (examples below) have been developed to provide more accurate estimations from limited data sets. Essentially this means joining up the measured performance points in the data set or look up table into a continuous surface to enable performance values to be extracted from intermediate points. These algorithms each have their own characteristic estimation accuracy.
- **Coulombic Efficiency**

  Coulomb counting is also subject to errors since all the Coulombs pumped into the battery during charging can not be converted into available charge. Some of the energy is inevitably lost in the chemical conversion process usually as heat. Similarly on the return trip, for the same reasons, some of the available charge is lost and only part of the stored charge is available for doing work. The round trip energy loss is about 3% for a Lithium battery. The Coulombic efficiency is the ratio between the discharge energy and the charging energy.

- **Self Discharge Rate**

  Another reason why all the energy put into the battery is not available to come out again is the self discharge of the cells. Self discharge of Lithium batteries is typically less than 3% per month so for periods of a day or so the effect is very small but it becomes more significant the longer the periods between charging and can be the source of accumulating errors unless the battery monitoring circuit is regularly reset or calibrated.
- **Random Errors** (Measurement Accuracy)

  Random errors arise from the inaccuracies in involved in measuring the factors which are actually taken into account in the SOC estimation. This applies to the cell characterisation as well as to the cells in the operating batteries, thus there are two potential sources of similar errors.
    - Cell voltage
    - Cell temperature
    - Battery current
    - Current sampling error
    - A to D converter quantising errors
    - Self discharge rate
    - Battery age / number of capacity turnovers (Cycles completed)

  Typically the net effect of a series of random errors such as those due to measurement inaccuracies can be calculated using the "Root Sum of Squares" method .
- **Cumulative Error Build Up**

  Over time the system "fully charged" reference point of the battery may drift so the system should be calibrated regularly to reset the reference SOC to 100% when the battery is fully charged. Regular calibration of the SOC estimation system is needed to avoid a cumulative error build up. This is particularly true for HEV batteries which under normal circumstances never reaches their fully charged condition when the system can be reset to a known level of charge.

Taking all these factors into consideration the SOC calculation could be subject to very large errors which could jeopardise the application unless steps are taken in the battery system design to mitigate these errors. The accuracy claimed for SOC calculation should be consistent with the combined measurement accuracies of the contributing parameters plus any offset errors. Manufacturer's claims of SOC accuracy of better than 5% are typical but this seems hard to justify considering the factors outlined here and errors may diverge even more as the cells grow older.
Compare this with the Accuracy Requirements above

Charge Estimation Algorithms

Several different techniques such as Fuzzy Logic, Kalman Filtering, Neural Networks and recursive, self-learning methods have been employed to improve the accuracy of the SOC estimation as well as the estimation of state of health (SOH).

Fuzzy Logic

Fuzzy Logic is simple way to draw definite conclusions from vague, ambiguous or imprecise information. It resembles human decision making with its ability to work from approximate data to find precise solutions.

Unlike classical logic which requires a deep understanding of a system, exact equations, and precise numeric values, Fuzzy logic allows complex systems to be modelled using a higher level of abstraction originating from our knowledge and experience. It allows expressing this knowledge with subjective concepts such as big, small, very hot, bright red, a long time, fast or slow. This qualitative, linguistic representation of the expert knowledge presents a natural rather than a numerical description of a system and allows relatively easy algorithm development compared to numerical systems. The outputs can then be mapped into exact numeric ranges to provide a characterisation of the system. Fuzzy logic is used extensively in automatic control systems.

Using this technique we can use all the information available to us about the performance of a battery to derive a more accurate estimation of its state of charge or the state of health. Software packages are available which simplify this process.

Kalman Filter

Kalman filtering addresses an age-old question: How do you get accurate information out of inaccurate data? More pressingly, How do you update a "best" estimate for the state of a system as new, but still inaccurate, data pour in? An HEV automotive application is an example of this situation. The battery SOC is affected by many simultaneous factors and is continually changing due to the user driving pattern. The Kalman filter is designed to strip unwanted noise out of a stream of data. It operates by predicting the new state and its uncertainty, then correcting this with a new measurement. It is suitable for systems subject to multiple inputs and is used extensively in predictive control loops in navigation and targeting systems. With the Kalman Filter the accuracy of the battery SOC prediction model can be improved and accuracies of better than 1% are claimed for such systems.

As with Fuzzy Logic, standard software packages are available to facilitate its implementation.

Neural Networks

A Neural Network is a computer architecture modelled upon the human brain's interconnected system of neurons which mimics its information processing, memory and learning processes. It imitates the brain's ability to sort out patterns and learn from trial and error, discerning and extracting the relationships that underlie the data with which it is presented.

Each neuron in the network has one or more inputs and produces an output; each input has a weighting factor, which modifies the value entering the neuron. The neuron mathematically manipulates the inputs, and outputs the result. The neural network is simply neurons joined together, with the output from one neuron becoming input to others until the final output is reached. The network learns when examples (with known results) are presented to it; the weighting factors are adjusted on the basis of data - either through human intervention or by a programmed algorithm-to bring the final output closer to the known result. In other words, neural networks "learn" from examples (as children learn to recognise dogs from examples of dogs) and exhibit some capability for generalisation beyond the training data.

Neural networks thus resemble the human brain in the following two ways:

1. A neural network acquires knowledge through learning.
2. A neural network's knowledge is stored within inter-neuron connection strengths known as synaptic weights.

The true power and advantage of neural networks lies in their ability to represent both linear and non-linear relationships and in their ability to learn these relationships directly from the data being modelled. Among the many applications are predictive modelling and control systems.

Neural Network techniques are useful in estimating battery performance which depends on quantifying the effect of numerous parameters most of which can not be defined with mathematical precision. Algorithms are refined with the aid of experience gained from the performance of similar batteries.

Consumer Battery Condition Indicators

Small primary cells are now available with a on-cell analogue SOC indicators known as battery testers or fuel gauges. On the side of the cell they incorporate a printed strip resembling a thermometer which provides a rough indication of the remaining capacity in the battery.

Based on thermochromic and conductive inks, a thin layer of conductive ink is applied in a wedge shape. The narrowest point indicates the lowest charge level and the widest area indicates a full charge. When the circuit is completed and current flows through the conductive ink and the resistance of the ink causes it to heat up. A small amount of current can generate enough heat to affect the smallest area of the wedge but as the area widens more current is needed to raise its temperature. The thermochromic ink printed on top of the conductive ink changes colour depending on the temperature and the extent of the colour change along the wedge indicates the magnitude of the current and hence the battery voltage.

The design is completed with a masking layer of normal ink which provides the illusion of a thermometer or analogue fuel gauge.

The measurement accuracy is dependent on the ambient temperature.

SOC of Capacitors

The state of charge of a capacitor is represented by the voltage across its terminals.

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Thermal Management

Temperature effects

Temperature Operating Limits

All batteries depend for their action on an electrochemical process whether charging or discharging and we know that these chemical reactions are in some way dependent on temperature. Nominal battery performance is usually specified for working temperatures somewhere in the + 20°C to +30°C range however the actual performance can deviate substantially from this if the battery is operated at higher or lower temperatures. See Temperature Characteristics for typical performance graphs.

Arrhenius Law tells us that the rate at which a chemical reaction proceeds, increases exponentially as temperature rises (See Battery Life). This allows more instantaneous power to be extracted from the battery at higher temperatures. At the same time higher temperatures improve electron or ion mobility reducing the cell's internal impedance and increasing its capacity.

At the upper end of the scale the high temperatures may also initiate unwanted or irreversible chemical reactions and / or loss of electrolyte which can cause permanent damage or complete failure of the battery. This in turn sets an upper temperature operating limit for the battery.

At the lower end of the scale the electrolyte may freeze, setting a limit to low temperature performance. But well below the freezing point of the electrolyte, battery performance starts to deteriorate as the rate of chemical reaction is reduced. Even though a battery may be specified to work down to -20°C or -30°C the performance at 0°C and below may be seriously impaired.

Note also that the lower temperature working limit of a battery may be dependent on its State of Charge. In a Lead Acid battery for instance, as the battery is discharged the Sulphuric Acid electrolyte becomes increasingly diluted with water and its freezing point increases accordingly.

Thus the battery must be kept within a limited operating temperature range so that both charge capacity and cycle life can be optimised. A practical system may therefore need both heating and cooling to keep it not just within the battery manufacturer's specified working limits, but within a more limited range to achieve optimal performance.

Thermal management however is not just about keeping within these limits. The battery is subject to several simultaneous internal and external thermal effects which must be kept within control.

Heat Sources and Sinks

Electrical Heating (Joule Heating)

The operation of any battery generates heat due to the I^2R losses as current flows through the internal resistance of the battery whether it is being charged or discharged. This is also known as Joule heating. In the case of discharging, the total energy within the system is fixed and the temperature rise will be limited by the available energy. However this can still cause very high localised temperatures even in low power batteries. No such automatic limit applies while charging as there is nothing to stop the user continuing to pump electrical energy into the battery after it has become fully charged. This can be a very risky situation.

Battery designers strive to keep the internal resistance of the cells as low as possible to minimise the heat losses or heat generation within the battery but even with cell resistances as low as 1milliOhm the heating can be substantial. See Effects of Internal Impedance for examples.

Thermochemical Heating and Cooling

In addition to Joule heating the chemical reactions which take place in the cells may be exothermic, adding to the heat generated or they may be endothermic, absorbing heat during the process of the chemical action. Overheating is therefore more likely to be a problem with exothermic reactions in which the chemical reaction reinforces the heat generated by the current flow rather than with endothermic reactions where the chemical action counteracts it. In secondary batteries, because the chemical reactions are reversible, chemistries which are exothermic during charging will be endothermic during discharging and vice versa. So there's no escaping the problem. In most situations the Joule heating will exceed the endothermic cooling effect so precautions still need to be taken.

Lead acid batteries are exothermic during charging and VRLA batteries are prone to thermal runaway (See below). NiMH cells are also exothermic during charging and as they approach full charge, the cell temperature can rise dramatically. Consequently, chargers for NiMH cells must be designed to sense this temperature rise and cut off the charger to prevent damage to the cells. By contrast Nickel based batteries with alkaline electrolytes (NiCads) and Lithium batteries are endothermic during charging. Nevertheless thermal runaway is still possible during charging with these batteries if they are subject to overcharging.

External Thermal Effects

The thermal condition of the battery is also dependent on its environment. If its temperature is above the ambient temperature it will lose heat through conduction, convection and radiation. If the ambient temperature is higher, the battery will gain heat from its surroundings. When the ambient temperature is very high the thermal management system has to work very hard to keep the temperature under control. A single cell may work very well at room temperature on its own, but if it is part of a battery pack surrounded by similar cells all generating heat, even if it is carrying the same load, it could well exceed its temperature limits.

Temperature - The Accelerator

The net result of the thermo-electrical and thermo-chemical effects possibly augmented by the environmental conditions is usually a rise in temperature and as we noted above this will cause an exponential increase in the rate at which a chemical reaction proceeds. We also know that if the temperature rise is excessive a lot of nasty things can happen

- The active chemicals expand causing the cell to swell
- Mechanical distortion of the cell components may result in short circuits or open circuits
- Irreversible chemical reactions can occur which cause a permanent reduction in the active chemicals and hence the capacity of the cell
- Prolonged operation at high temperature can cause cracking in plastic parts of the cell
- The temperature rise causes the chemical reaction to speed up increasing the temperature even more and could lead to thermal runaway
- Gases may be given off
- Pressure builds up inside the cell
- The cell may eventually rupture or explode
- Toxic or inflammable chemicals may be released
- Law suits will follow

Thermal Capacity - The Conflict

It is ironic that as battery engineers strive to cram more and more energy into ever smaller volumes, the applications engineer has increasing difficulty to get it out again. The great strength of new technology batteries is unfortunately also the source of their greatest weakness.

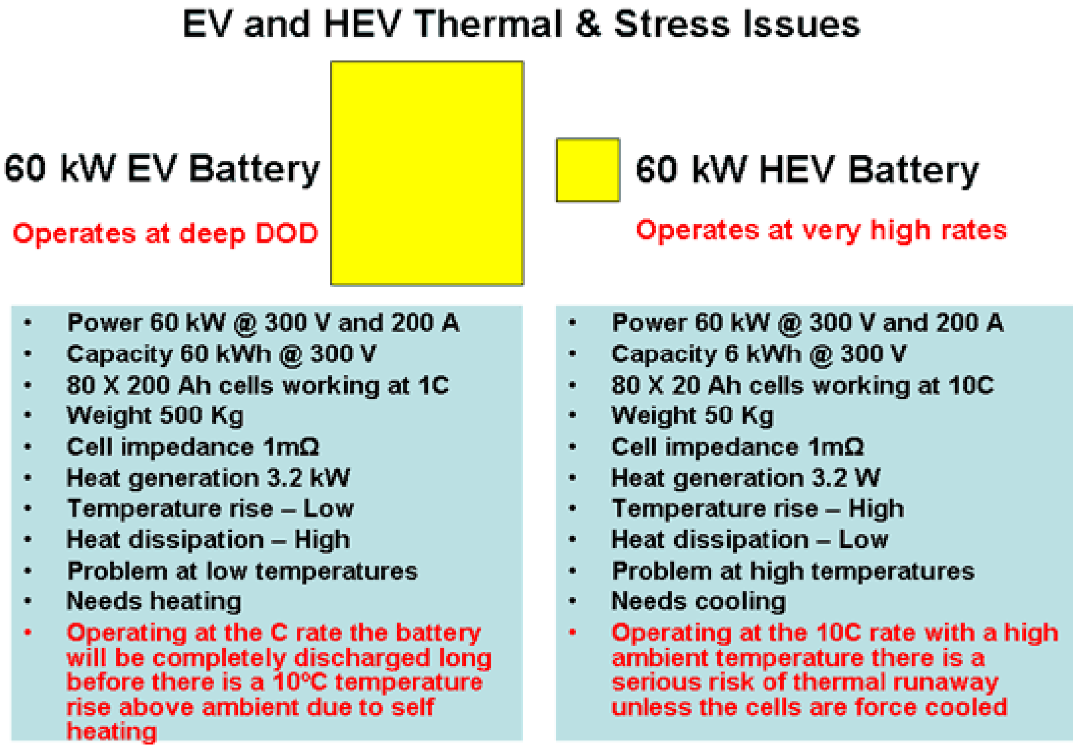
The thermal capacity of an object defines its ability to absorb heat. In simple terms for a given amount of heat, the bigger and heavier the object is, the smaller will be the temperature rise caused by the heat.

For many years lead acid batteries have been one of the few power sources available for high power applications. Because of their bulk and weight, temperature rise during operation has not been a major problem. But in the quest for smaller, lighter batteries with higher power and energy densities, the unavoidable consequence is that the thermal capacity of the battery will be decreased. This in turn means that for a given power output, the temperature rise will be higher.

(This assumes a similar internal impedance and similar thermochemical properties which might not necessarily be the case.) The result is that heat dissipation is a major engineering challenge for high energy density batteries used in high power applications. Cell designers have developed innovative cell construction techniques to get the heat out of the cell. Battery pack designers must find equally innovative solutions to get the heat out of the pack.

EV and HEV Battery Thermal Considerations

Similar conflicts occur with EV and HEV batteries. The EV battery is large with good heat disipation possibilities by convection and conduction and subject to a low temperature rise due to its high thermal capacity. On the other hand the HEV battery which must handle the same power is less than one tenth of the size with a low thermal capacity and low heat dissipation properties which means it will be subject to a much higher temperature rise.



EV and HEV Thermal & Stress Issues

60 kW EV Battery

Operates at deep DOD

- Power 60 kW @ 300 V and 200 A
- Capacity 60 kWh @ 300 V
- 80 X 200 Ah cells working at 1C
- Weight 500 Kg
- Cell impedance 1mΩ
- Heat generation 3.2 kW
- Temperature rise – Low
- Heat dissipation – High
- Problem at low temperatures
- Needs heating
- Operating at the C rate the battery will be completely discharged long before there is a 10°C temperature rise above ambient due to self heating

60 kW HEV Battery

Operates at very high rates

- Power 60 kW @ 300 V and 200 A
- Capacity 6 kWh @ 300 V
- 80 X 20 Ah cells working at 10C
- Weight 50 Kg
- Cell impedance 1mΩ
- Heat generation 3.2 W
- Temperature rise – High
- Heat dissipation – Low
- Problem at high temperatures
- Needs cooling
- Operating at the 10C rate with a high ambient temperature there is a serious risk of thermal runaway unless the cells are force cooled

Taking into account the need to keep the cells operating within their allowable temperature range (See Cycle Life in the section on Lithium Battery Failures) the EV battery is more likely to encounter problems to keep it warm at the low end of the temperature range while the HEV battery is more likely to have overheating problems in high temperature environments even though they both dissipate the same amount of heat.

In the case of the EV, at very low ambient temperatures, self heating (I^2R heating) by the current flow during operation will most likely be insufficient to raise the temperature to the desired operating levels because of the battery's bulk and external heaters may be required to raise the temperature. This could be provided by diverting some of the battery capacity for heating purposes. On the other hand, the same heat generation in the HEV battery working in high temperature environments could send it into thermal runaway and forced cooling must be provided.

See also EV, HEV and PHEV Specifications in the Traction Battery section

Thermal Runaway

The operating temperature which is reached in a battery is the result of the ambient temperature augmented by the heat generated by the battery. If a battery is subject to excessive currents the possibility of thermal runaway arises resulting in catastrophic destruction of the battery. This occurs when the rate of heat generation within the battery exceeds its heat dissipation capacity. There are several conditions which can bring this about:

- Initially the thermal I^2R losses of the charging current flowing through the cell heat up the electrolyte, but the resistance of the electrolyte decreases with temperature, so this will in turn result in a higher current driving the temperature still higher, reinforcing the reaction till a runaway condition is reached.

- During charging the charging current induces an exothermic chemical reaction of the chemicals in the cell which reinforces the heat generated by the charging current.
- Or during discharging the heat produced by the exothermic chemical action generating the current reinforces the resistive heating due to the current flow within the cell.
- The ambient temperature is excessive.
- Inadequate cooling

Unless some protective measures are in place the consequences of the thermal runaway could be meltdown of the cell or a build up of pressure resulting an explosion or fire depending on the cell chemistry and construction. See more details in the section on Lithium Battery Failures.

The thermal management system must keep all of these factors under control.

Note

Thermal runaway can occur during the charging of valve regulated lead acid batteries where gassing is inhibited and the recombination adds to the temperature rise. This does not apply to flooded lead acid batteries because the electrolyte boils off.

Temperature Controls

Heating

Low temperature operating conditions are relatively easy to cope with. In the simplest case there is usually enough energy in the battery to power self heating elements which gradually bring the battery up to a more efficient operating temperature when the heaters can be switched off. In some cases it is enough to keep the battery on its recharging cycle when it is not in use. In more complex cases for example with high temperature batteries such as the Zebra battery running at temperatures well above normal ambient temperatures some external heating may be required to bring the battery up to its operating temperature on start up and special thermal insulation may be needed to maintain the temperature for as long as possible after it has been switched off.

Cooling

For low power batteries the normal protection circuits are sufficient to keep the battery within its recommended operating temperature limits. High power circuits however need special attention to thermal management.

Design objectives

- Protection From Overheating -

  In most cases this simply involves monitoring the temperature and interrupting the current path if the temperature when the temperature limits are reached using conventional protection circuits. While this will prevent damage to the battery from overheating it can however cut off the battery before its current carrying limit is reached seriously limiting its performance.
- Dissipation of Surplus Heat Generated -

  Removing heat from the battery allows higher currents to be carried before the temperature limits are reached. Heat flows out of the battery by convection, conduction and radiation and the pack designer's task is to maximise these natural flows by keeping the ambient temperature low, by providing a solid, good heat conducting path from the battery (using metallic cooling rods or plates between the cells if necessary), by maximising its surface area, by providing good natural air flow through or around the pack and by mounting it on a conductive surface.
- Uniform Heat Distribution -

  Even though the battery thermal design may be more than sufficient to dissipate the total heat generated by the battery, there could still be localised hot spots within the battery pack which can exceed the specified temperature limits. This can be a problem with the cells in the middle of a multi cell pack which will be surrounded by warm or hot cells compared with the outer cells in the pack which are facing a cooler environment. Separating the cells to avoid this problem adds to the volume of the pack. Thermal imaging may be needed to identify potential problem areas.
- Minimum Addition to the Weight -

  For very high power applications, such as traction batteries used in EVs and HEVs, natural cooling may be insufficient to maintain a safe working temperature and forced cooling may be required. This should be the last resort as it complicates the battery design, adds weight to the battery and consumes power. If forced cooling is unavoidable however, the first choice would normally be forced air cooling using a fan or fans. This is relatively simple and inexpensive but the thermal capacity of the thermal fluid, air, which is intended to carry the heat away is relatively low limiting its effectiveness. In the worst case liquid cooling may be required.

  For very high cooling rates working fluids with a higher thermal capacity are required. Water is normally the first choice because it is inexpensive but other fluids such as ethylene glycol (anti freeze) which have a better thermal capacity may be used. The weight of the coolant, the pumps to circulate it, the cooling jackets around the cells, the pipework and manifolds to carry and distribute the coolant and a radiator or heat exchanger to cool it, all add dramatically to the total weight, complexity and cost of the battery. These penalties could well outweigh the gains expected to be achieved by using high energy density battery chemistries.

Heat Recovery

In some applications, such as electric vehicles as noted above, there is the opportunity to use the waste heat for heating the passenger compartment and most automotive systems include some form of integrating the battery thermal management with the vehicle climate controls. This is however only beneficial during cold weather. In hot climates the high ambient temperature places an added burden on the battery thermal management.

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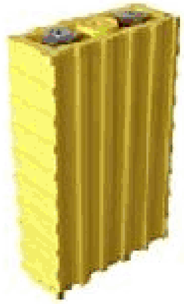
Cell Construction

Components

The basic components of a battery are the electrodes with terminals to connect to the external circuit, a separator to keep the electrodes apart and prevent them from shorting, the electrolyte which carries the charged ions between the electrodes and a case to contain the active chemicals and hold the electrodes in place.

- **Case**

  The case may simply be a robust container made from glass, plastic or metal, insulated from the electrodes, which does not form part of the current path through the battery. Lead acid batteries typically have such containers. A metallic case however can be used as one of the electrodes, saving materials, as in the case of Leclanché (Zinc- Carbon) cells. Examples of the range of cases used for rechargeable Lithium cells are shown below.



Plastic case

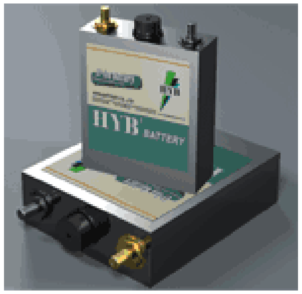
Robust. Easy packaging, Flammable, Inexpensive. Stacked or jelly roll electrodes. Retains heat, Poor thermal dissipation, Sizes up to 1000AH.

Used by: Thunder Sky, International Battery, China Hipower, HuanYu

Cylindrical steel case

Robust. High energy density cells but packs wasteful of space, Space allows cooling air flow, Expensive, Sizes up to 200 Ah

Used by: Gaia, PHET, LifeBatt, BAK, SAFT, A123



Prismatic metal case (Steel / Aluminium)

Robust, Easy packaging, Good space utilisation, Expensive, Jelly roll or stacked electrodes. High energy density, Good heat dissipation, Sizes up to 200 Ah

Used by: BYD, HYB, Lishen, Toshiba, Varta

Pouch cell - Also known as **Lipo cells**

Vulnerable, Inexpensive, Design freedom on dimensions, Difficult packaging, High energy density but reduced by support packaging needed, Prone to swell and leak, Less danger of explosion (cell bursts), Good heat dissipation, Made in very high volumes, Economical for small volumes, Sizes up to 240 Ah

Used by: Kokam, BAHUP, ATL, Yoku, EIG, Enerdel, LG and many others

Small cylindrical and prismatic cells

Metal cans, Low cost products in standard shapes, Made in very high volumes, Complex and expensive packaging and BMS electronics due to low unit capacity, Sizes up to 5 Ah.

Used by: ATL, BAK, B&K, BYD, Lishen, Panasonic, Sony, Sanyo, Toshiba, Samsung, Valence and many others

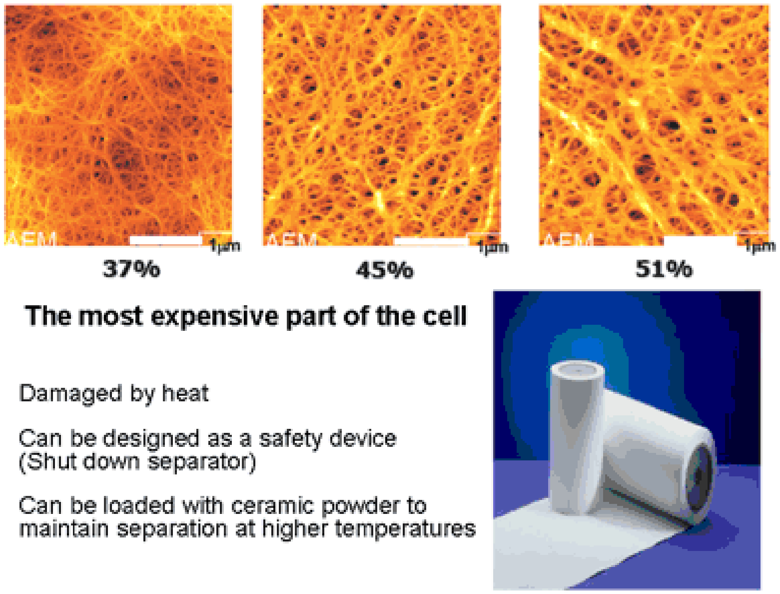
- **Electrodes**

  The electrodes material may be a rigid metallic grids as in Lead acid batteries or the active electrode material may impregnated into or coated onto a spiral rolled metallic foil which simply acts as a current collector as in many Nickel and Lithium based cells. See also Battery Manufacturing

- **Separator**

  The separator may be a mechanical spacer, fibreglass cloth or a flexible plastic film made from nylon, polyethylene or polypropylene. It must be porous and very thin to permit the charged ions to pass without impediment and it should take up the minimum of space to allow for the maximum use of the available space for the active chemicals. At the same time it must be resistant to penetration by burrs or dendrite growths on the electrode plates or from contamination of the electrode coating to prevent the possibility of short circuits between the electrodes. These characteristics should be maintained at high operating temperature when softening of the plastic material could clog the pores or reduce its resistance to penetration. The breakdown or penetration of the separator is a potential area of weakness in high power cells and special separator materials have been developed to overcome this problem.

The Separator .



The most expensive part of the cell

Damaged by heat

Can be designed as a safety device (Shut down separator)

Can be loaded with ceramic powder to maintain separation at higher temperatures

- **Terminals**

  There are many ways of connecting to the electrodes ranging from spring contacts, through wires or tags to mechanical studs. The main requirement is that the terminals should be able to handle the maximum current without overheating, either the terminal itself or the electrode connected to it. This needs careful design of the connection to the electrodes to take off the current through the maximum possible area of electrode material so as not to cause any hot spots. See also notes about external connections in the section on Battery Pack Design.

- **Electrolyte**

  For many years all electrolytes were in aqueous or gel form. Recently solid polymer electrolytes have been developed which do not suffer from leakage or spillage. As well as being safer in case of an accident and they also bring new degrees of freedom to cell design allowing mechanical designs to be shaped to fit into odd shaped cavities. Polymer electrolytes are typically used in Lithium batteries.

Internal Construction

Broadly speaking the cell voltage is controlled by the cell chemistry, the capacity is governed by the weight of the active chemicals and the current carrying capacity (or power) is governed by the area of the electrodes. To a lesser extent all three of the above parameters as well as the thermal properties are affected by the internal impedance of the cell and this depends on the conductivity of the electrolyte and the layout and resistance of the components in the current path.

Thus the size shape and materials used in its construction all affect the ultimate electrical performance of a cell.

Electrodes (Energy/Power Trade-Offs)

For a given cell chemistry and within the space available inside a given cell case, the cell performance can be optimised for capacity or power.

- Increasing the surface area of the electrodes increases the cell's current handling capability. Thus the cell can both deliver more power and it can be charged more quickly.
- Increasing the volume of electrolyte in the cell increases the cell's energy storage capacity.

The prime trade off is between the area of the electrodes and the volume of the electrolyte which can be contained within the volume available in the cell case.

High power cells require electrodes with a large surface area as well as enlarged current collectors which take up more of the available space within a given cell, displacing the electrolyte and reducing the cell capacity.

The effective surface area of an electrode can be increased without increasing its physical size by making its surface porous and using materials with very fine particle size. This can increase the effective surface area of the electrodes by 1000 to 100,000 times enabling higher current rates to be achieved.

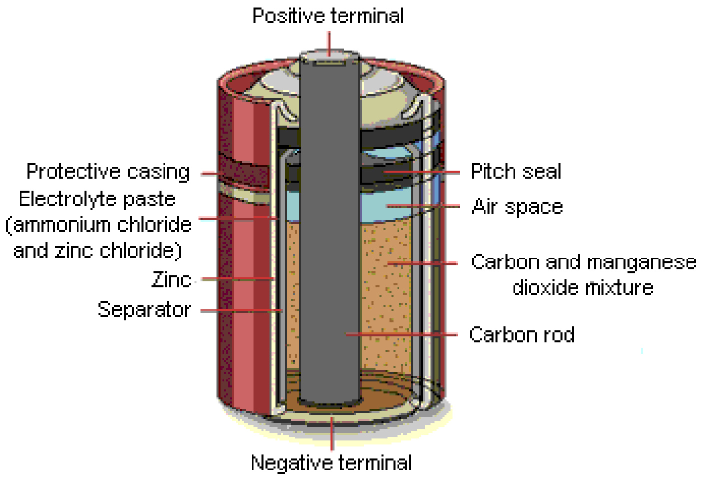
High capacity cells require large volumes of electrolyte which must be accommodated between the electrodes. This has a double effect in reducing the cell power handling capability. First, the electrodes must be smaller and further apart to make space for the extra electrolyte and hence they can carry less current. Secondly, because of the increased volume of the electrolyte, it takes longer for the chemical actions associated with charging and discharging to propagate completely through the electrolyte to complete the chemical conversion process. (More details are given in the section on Charging Times).

As an example - Lithium Ion cells optimised for capacity may typically handle peak currents of 2C or 3C for short periods, whereas Lithium Ion cells optimised for power could possibly deliver pulsed currents of 30C to 40C.

Four of the most common constructions are shown below. Over the years there have been many thousands of variants of these basic types used for many different cell chemistries.

High power cells usually incorporate special safety devices. See **"Designed in" safety measures**.

Bobbin Electrodes

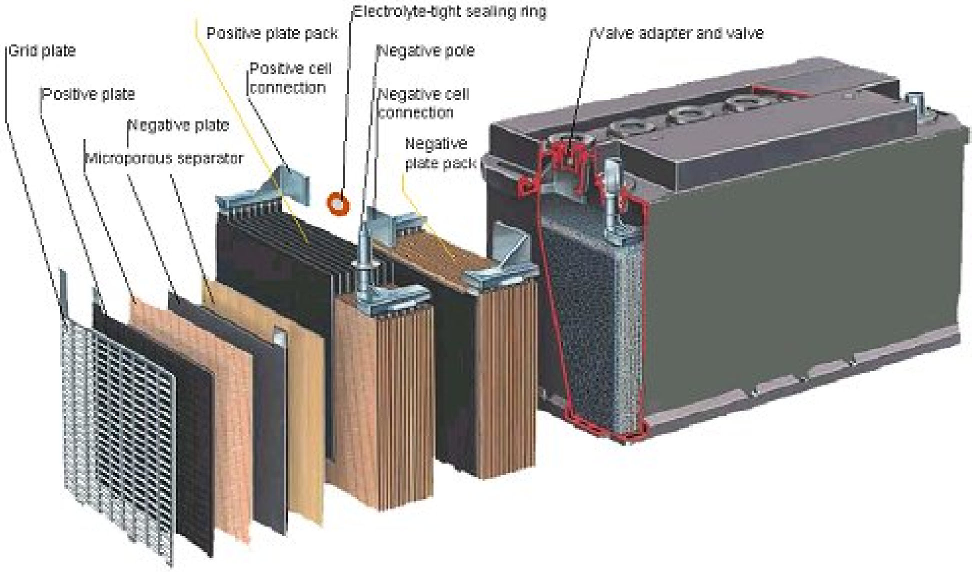


Zinc - Carbon (Leclanché) Cell

The bobbin construction has been used for over a century since the introduction of the Zinc- Carbon (Leclanché) Cell and a more recently with the newer Alkaline cells which use a more complex version of this type. It is a cylindrical construction utilizing an internal cylindrical electrode usually in the form of a rod which is immersed in the electrolyte which is in turn contained in an external electrode in the form of a cylindrical cup arranged as a sleeve inside the cell container. A separator sheath prevents contact between the electrodes.

Its advantage is that it is simple, it stores a large amount of electrolyte which gives it a high capacity and hence long life but the electrode surfaces are very small which results in a high internal resistance and limits the currents it can deliver. However, this small area also results in a low rate of self discharge and these batteries therefore have a long shelf life. It is ideal for many applications requiring primary cells and is manufactured in very large quantities.

Flat Plate Electrodes

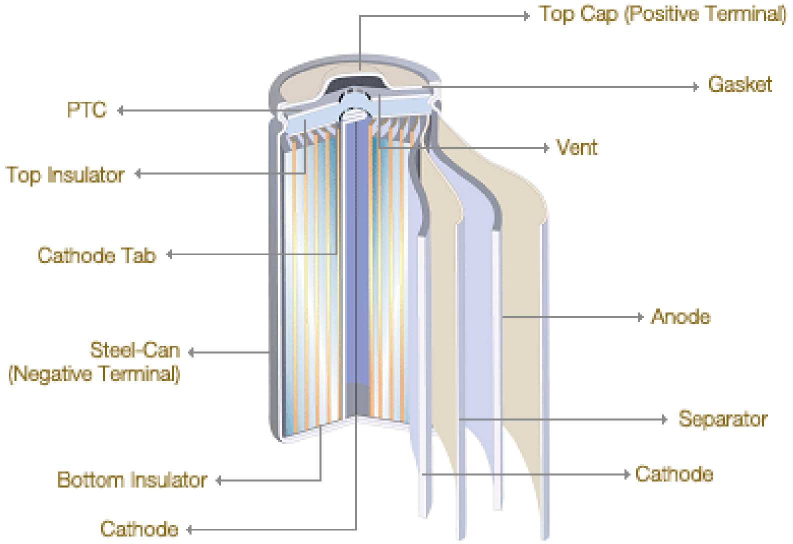


Cells Used in Lead Acid Battery

Source Eurobat

Flat plate cells typically used in Lead Acid batteries also have over a hundred years of history and development. The electrodes are made in the form of flat plates suspended in the electrolyte which is held in a suitable container which does not usually take part in the chemical reaction. A separator between the plates prevents them from touching eachother and short circuiting. This is another simple construction which is also used by many different cell chemistries. Its main advantage is that it can be scaled up to very large sizes, larger plates providing for higher currents and larger containers allowing high storage capacities.

Spiral Wound Electrodes (Also called Jelly-roll or Swiss-roll construction)



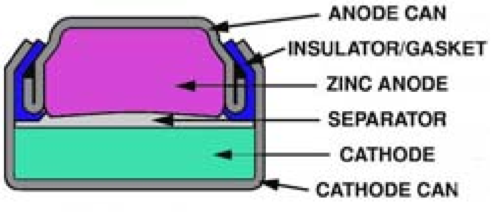
LG Spiral Wound Cylindrical Cell

In the quest for higher current carrying capacity, it is necessary to increase the active surface area of the electrodes, however the cell case size sets limits on the size of electrodes which can be accommodated. One way of increasing the electrode surface area is to make the electrodes and the separator from long strips of foil and roll them into a spiral or cylindrical jelly-roll shape. This provides very low internal resistance cells. The downside is that since the electrodes take up more space within the can there is less room for the electrolyte and so the potential energy storage capacity of the cell is reduced. This construction is used extensively for secondary cells. The example above shows a Lithium-Ion cell but this technology is also used for NiCads, NiMH and even some Lead acid secondary cells designed for high rate applications.

Spiral wound construction not limited to cylindrical shapes. The electrodes can be wound onto a flat mandrel to provide a flattened shape which can fit inside a prismatic case. The cases may be made from aluminium or steel.

This construction is ideally suited for production automation.

Button Cells and Coin Cells



ZINC-ANODE CELL

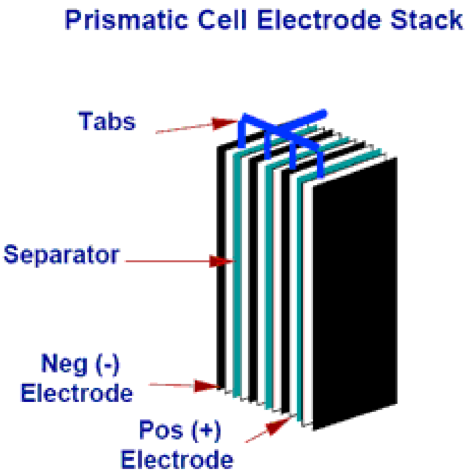
Most button and coin cells follow the same basic layout in their construction as shown in the diagram above. They are used where small size is required. As with bobbin cells they have a relatively high capacity but deliver low power.

Multiple Electrode Cells

- **Monopolar configuration**

  In this configuration the battery is constructed form individual cells with external connections joining the cells to form series and parallel chains.

- **Stacked Electrodes**

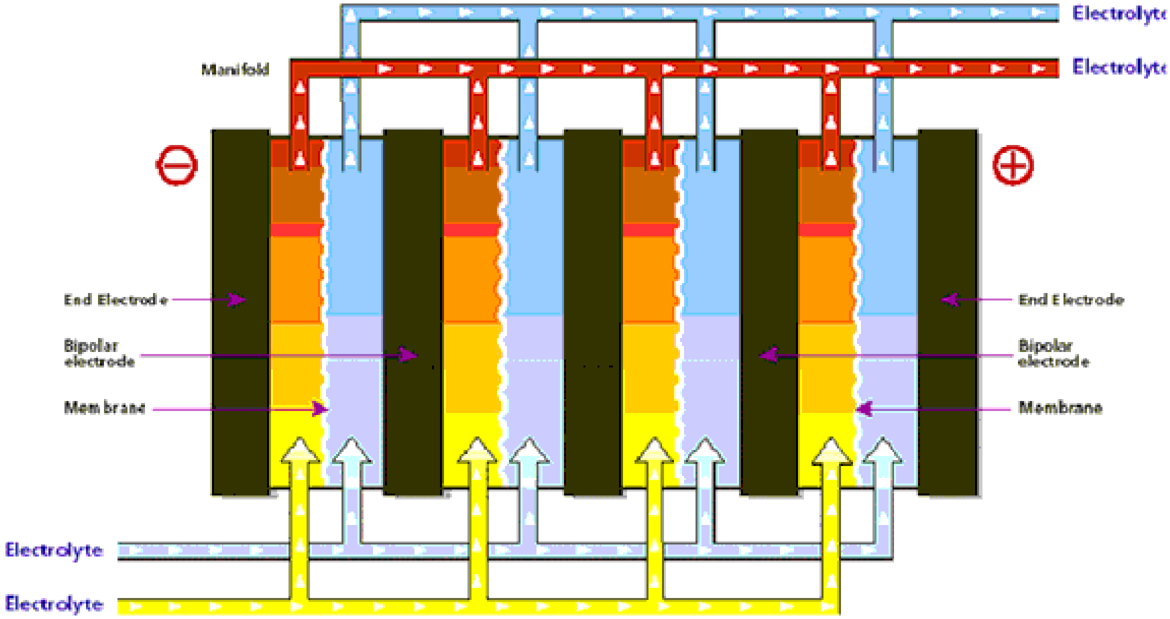


This is an example of monopolar configuration. Reminiscent of Volta's pile, the positive and negative plates are sandwiched together in layers with separators between them, inserted into the case, and sealed. This construction provides an energy efficient form factor and is typically used in high power Lithium Polymer cells with the solid polymer electrolyte separating the cells.

- **Bipolar configuration**

  In bipolar batteries the cells are stacked in a sandwich construction so that the negative plate of one cell becomes the positive plate of the next cell. Electrodes, often called duplex electrodes, are shared by two series-coupled electrochemical cells in such a way that one side of the electrode acts as an anode in one cell and the other side acts as a cathode in the next cell. The anode and cathode sections of the common electrodes are separated by an electron-conducting membrane which does not allow any flow of ions between the cells and serves as both a partition and series connection.

  This is an efficient design which reduces the number of plates and eliminates external connections, reduces the weight of the battery, increases the energy density and reduces costs. The current pathway is also shorter and resistance losses will be less enabling the battery to handle higher power. Bipolar construction is usually adopted for Fuel Cells and Flow Batteries in which the electrolyte flows over, or is pumped through the cells, but the technique has recently been trialled on much simpler, smaller scale automotive and portable batteries with several other cell chemistries using single electrolytes.



Bipolar Cell Construction In a Flow Battery Source: Regenesys

Bipolar cells suffer from higher self discharge due the shunt current which occurs through the electrolyte manifold because the electrodes of the same polarity are at different potentials.

Bipolar batteries are also called "Layer Cells" and "Stacked Wafer Cells"

Electrode Interconnections

The internal resistance of the cell and the distribution of the currents and potentials within the cell are affected by the cell geometry which must be optimised to provide robust connections, minimum length current paths, and even distribution of currents to avoid local hot spots and uneven potentials which could give rise to unbalanced, damaging chemical reactions at different parts of the electrodes.

Sealed Cells and Recombinant Cells

Most batteries these days seal the electrolyte into the cell case. This is to prevent leakage of electrolyte and to prevent any gaseous products of charging and discharging from escaping into the atmosphere. The cell may also include a catalyst to promote recombination of these gaseous products. Such cells are called recombinant cells.

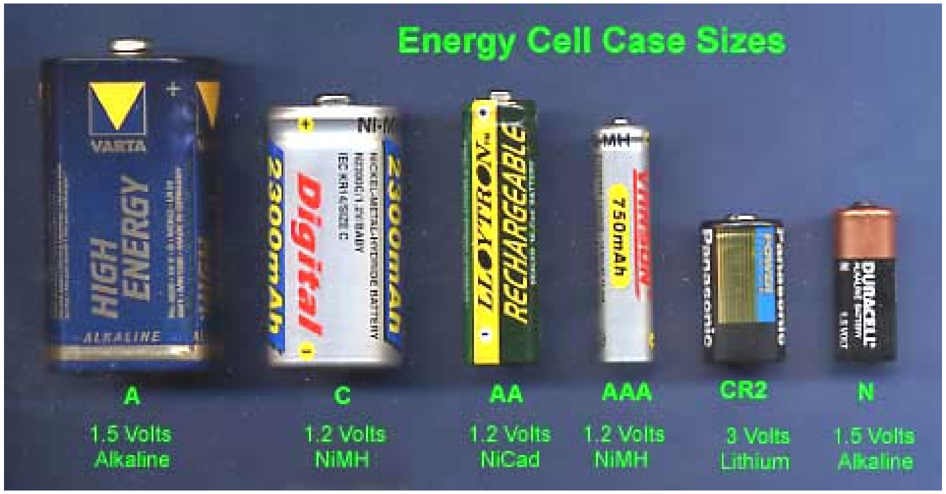
Safety Vents

When a cell is sealed, high internal pressures may build up due to the release of gases and due to expansion caused by high temperatures. As a safety precaution sealed cells usually incorporate a safety vent to allow excess pressure to be reduced in a controlled way.

Cell Casing

As with the internal cell construction there are many variants of case designs. Some standard, low power packages are shown below.

Cylindrical Cells



The picture above shows the most common cylindrical cell sizes from a range of manufacturers. The shapes may be standardized but the voltages and chemistries are not. The four largest sizes can each house Leclanché, Alkaline, NiCad, NiMH and Lithium chemistries with voltages ranging from 1.2 to 3.7 Volts. The first two chemistries are used for primary cells and are based on a bobbin construction. The remaining chemistries are used for secondary cells with spiral wound electrodes. Care is needed to match the chargers to the appropriate cells.

Cylindrical cells provide strong mechanical stability, good energy density and low costs.

It is estimated that 90% of portable, battery-operated devices require AA, C, or D battery sizes.

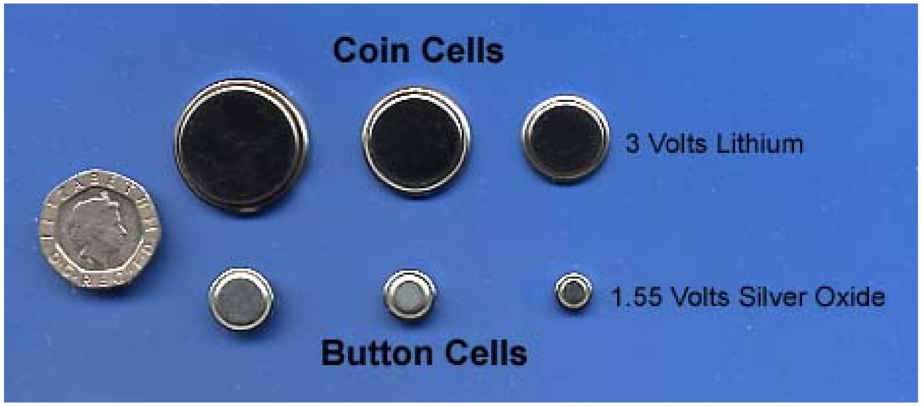
Multi-cell Batteries

The two batteries shown above are actually made up from groups of cylindrical cells. The type 23A contains eight 1.5 Volt cells and the PP3 contains six 1.5 Volt cells.

Common Household-Battery Sizes

Size	Shape and Dimensions
D	Cylindrical, 61.5 mm tall, 34.2 mm diameter.
C	Cylindrical, 50.0 mm tall, 26.2 mm diameter.
AA	Cylindrical, 50.5 mm tall, 14.5 mm diameter.
AAA	Cylindrical, 44.5 mm tall, 10.5 mm diameter.
PP3	Rectangular, 48.5 mm tall, 26.5 mm wide, 17.5 mm deep.

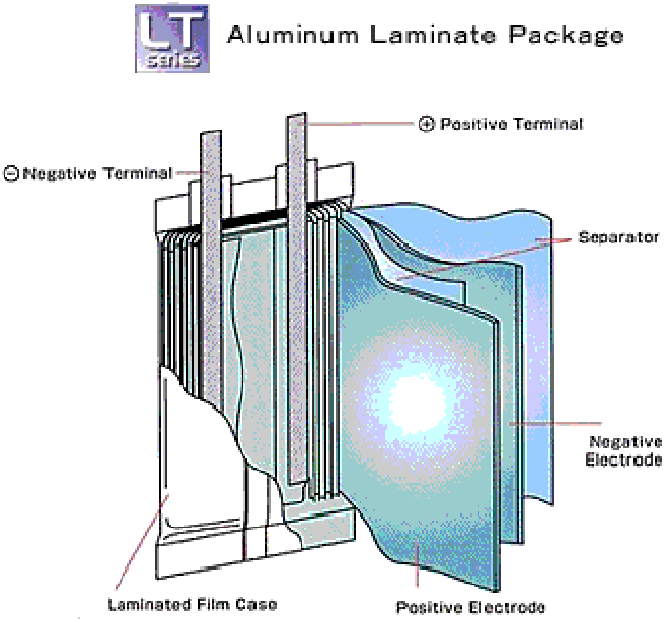
Button Cells and Coin Cells



Button and coin cells are available in a range of sizes, voltages and cell chemistries. (Zinc -Air cells are also available but not shown)

Pouch Cells

Valence pouch cells

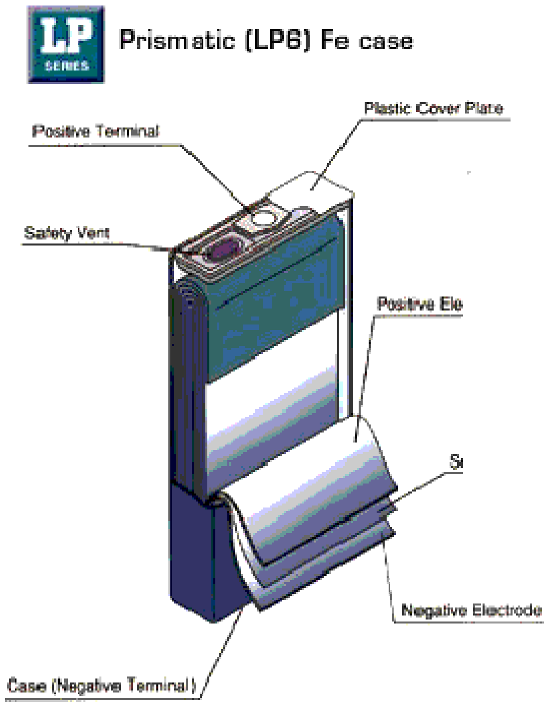


Pouch casings are typically used for Lithium Polymer cells with solid electrolytes, providing a low cost "flexible" (sometimes in unintended ways) construction. The the electrodes and the solid electrolyte are usually stacked in layers or laminations and enclosed in a foil envelope. The solid electrolyte permits safer, leak-proof cells. The foil construction allows very thin and light weight cell designs suitable for high power applications but because of the lack of rigidity of the casing the cells are prone to swelling as the cell temperature rises. Allowance must be made for the possibility of swelling when choosing cells to fit a particular cavity specified for the battery compartment. The cells are also vulnerable to external mechanical damage and battery pack designs should be designed to prevent such possibilities.

The GS-Melcotec example illustrated uses spiral wound electrodes and a solid polymer electrolyte.

This construction, using stacked electrodes is suitable for making odd shaped cells but few applications make use of this opportunity.

Prismatic Cells



Prismatic cells are contained in a rectangular can. The electrodes are either stacked or in the form of a flattened spiral. They are usually designed to have a very thin profile for use in small electronic devices such as mobile phones. Prismatic cells provide better space utilisation at the expense of slightly higher manufacturing costs, lower energy density and more vulnerability to swelling, but these are minor effects which don't constitute a major disadvantage.

This example from GS-Melcotec has a steel can with spiral wound electrodes and a liquid electrolyte.

Thin Film Batteries

Thin film printing technology is now being used to apply solid state Lithium polymer chemistry to a variety of substrates to create unique batteries for specialist applications. Thin film batteries can be deposited directly onto chips or chip packages in any shape or size, and flexible batteries can be made by printing on to plastics, thin metal foil or even paper. Because of their small size, the energy storage and current carrying capacity of thin film batteries is low but they have unique properties which distinguish them from conventional batteries including:

- All solid state construction

- The battery can be integrated into the circuit for which it provides the power
- Bendable batteries are possible
- Can be made in any shape or size
- Long cycle life and operating life
- Operate over wide temperature range
- High energy and power densities
- Cost and capacity are proportional to the area
- No safety problems

Thin film batteries have a wide range of uses as power sources for consumer products and for micro-sized applications.
The battery on the right from Oak Ridge Micro-Energy is designed for use in implantable medical devices.

Other applications include non-volatile memory backup and sensors.

Flexible film batteries like that shown on the left from Infinite Power Solutions are suitable for powering smart cards and radio frequency identification (RFID) tags.

Under development for ten years, thin film batteries are just recently becoming available in commercial quantities.

High Power Batteries

While there is at least some standardisation with low power cells, the same can not be said for high power cells which are made in a wide range of sizes using many different construction techniques. These include foil pouches, plastic or glass box like structures and cylindrical steel tubes.

The large cells on the right are 3.7 Volt Lithium cells. The cylindrical cell has a capacity of 60 Ah, while the prismatic cell has a 200 Ah capacity.

The small cells in the foreground for comparison purposes are AAA size.

Low internal resistance is an important requirement of these cells and this in turn requires thick current carriers and low contact resistances between the electrodes and the interconnections. Because these cells are designed to carry high currents which cause them to heat up, the cells usually incorporate features to allow for expansion of the contents and to avoid swelling. There may be voids inside the cell or there could be special clamps around the outside of the cells to constrain expansion to a particular direction.

Timescales and Costs

In order to achieve economical market shares and at the same time guarantee high quality standards, cells are generally manufactured on high volume automated production lines. The timescale to develop and prove out an all new battery technology can be typically ten years and the costs of setting up a production line to manufacture the new batteries can be anywhere from $100 million to $300 million or more. Sales volumes need to be in the hundreds of millions to break even.

Nomenclature

Cell identification.

There is considerable confusion about naming standards for cells with different systems used in Europe, the USA and Japan as well as manufacturers ' own standards.

One convention is two letters followed by a series if numbers.

The first letter represents the cell chemistry. The second letter represents the shape of the cell.

The numbers represent the dimensions of the cell in millimetres. For cylindrical cells the first two digits are the diameter and the remaining digits the length. For prismatic cells the first two digits represent the thickness, the second pair the height and the last pair the width.

Because of the plethora of "standards" the only safe course in identifying a cell is to consult the manufacturers' data sheets.

Examples

- **Common Primary Cells**

See Battery Case Sizes for dimensions of common primary cells.

- **Cylindrical Cells**

  LC18650 is a common Li-ion cell in a Cylindrical can   Size (diameter18mm height 65.0mm)

See Cylindrical Cell Sizes for a listing of typical cylindrical cell sizes and capacities

- **Prismatic Cells**

  LP083448 is a Li-ion cell in a Prismatic can   Dimensions(thickness 8mm height 48mm width 34 mm)

See Prismatic Cell Sizes for a listing of typical prismatic cell sizes and capacities.

See Power Cell Sizes for examples of high power prismatic cells. (High power cylindrical cells are also available)

See also Battery Pack Design

Woodbank Communications Ltd, South Crescent Road, Chester, CH4 7AU, (United Kingdom)

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Alternative Energy Storage Methods

A brief diversion

Several non chemical energy storage techniques have been developed over the years, mostly for very high power applications and while all of them have been used in practical systems, apart from capacitors, there has been slow take up of the ideas up to now. Some examples are given here.

Capacitors - The Electrostatic Battery

The use of capacitors for storing electrical energy predates the invention of the battery. Eighteenth century experimenters used Leyden jars as the source of their electrical power.

Capacitors store their energy in an electrostatic field rather than in chemical form. They consist of two electrodes (plates) of opposite polarity separated by an electrolyte. The capacitor is charged by applying a voltage across the terminals which causes charge to migrate to the surface of the electrode of opposite polarity.

The energy stored is related to the charge at each interface, **q** (Coulombs) , and potential difference, **V** (Volts), between the electrodes. The energy, **E** (Joules), stored in a capacitor with capacitance **C** (Farads) is given by the following formula.

$$\mathbf{E = \tfrac{1}{2}\, q\, V = \tfrac{1}{2}\, C V^2}$$

See What can a Joule do? for an example.

Since capacitors store charge only on the surface of the electrode , rather than within the entire electrode, they tend to have lower energy storage capability and lower energy densities. The charge/discharge reaction is not limited by ionic conduction into the electrode bulk, so capacitors can be run at high rates and provide very high specific powers but only for a very short period. Typical numbers for capacitors and batteries are given below:

Capacitor / Battery Comparison

Device	Energy density Wh/L	Power density W/L	Cycle life Cycles	Discharge time Seconds
Batteries	50-250	150	1 - 10^3	> 1000
Capacitors	0.05 - 5	10^5 - 10^8	10^5 - 10^6	<1

See also examples of the relative energy storage capacities of capacitors and batteries in the section on Short Circuits.

Since there is no chemical reactions are involved, the charge/discharge reactions can typically be cycled many more times than batteries (10^8 cycles per device have been achieved). For the same reason, capacitors don't require any special charging circuits and cells can be designed to accept very high voltages, although for very high capacities the working voltage is limited to a few volts.

Supercapacitors are simply capacitors employing plates with extremely high surface areas providing a high storage capacity. Maximizing the surface area of the electrodes within the available space means the thickness of the dielectric must be minimised. This in turn limits the maximum working voltage of the capacitor. For this reason, even though there is no fixed limit, set by the chemistry, on the working voltage of a capacitor as there is with batteries, for supercapacitors with a capacitance of over 1000 Farads or more the working voltage may be only a few volts.

For high voltage applications such as electric vehicles, a series chain of capacitors must be used to avoid exceeding the working voltage of individual capacitors and this reduces the effective capacity of the chain. For a series chain of N equal value capacitors the capacity is calculated from $C=c/N$ where C is the capacitance of the chain and c is the capacitance of the individual capacitors. At the same time, the internal resistance of the chain is increased to $R=rN$, where r is the internal resistance of the capacitor, as more capacitors are added. This slows the charge-discharge rate and increases the losses.

Higher capacitances can be achieved by using parallel capacitors. In this case the capacitance of a group of N parallel capacitors is given by $C=Nc$. At the same time the resistance of the group is reduced and is given by $R=r/N$.

Capacitors are now used extensively as power back up for memory circuits and in conjunction with batteries to provide a power boost when needed. See Load sharing.

High power versions can provide high instantaneous power but they have limited capacity. See the Ragone Plot below. They are suitable for applications which require a short duration power boosts such as UPS systems which need fast take over of substantial electrical loads for a short period until back up power units, such as rotary generators or fuel cells, have switched on and reached their full output. Similarly they can be used to provide an instantaneous power boost in Electric and Hybrid vehicles.

Supercapacitors are however also ideal for absorbing the energy generated from regenerative braking in EVs and HEVs since they can accept very high instantaneous charge rates which would exceed the recommended maximum charge rate of the batteries. Used in conjunction with batteries the capacitors enable the full regenerative charge to be captured, avoiding the wasteful dumping of the excess charge which the batteries are unable to accommodate.

See more in the section on Capacitors and Supercapacitors.

History (Electrolytic Capacitors)

Heat - The Thermal Battery

There are two types of thermal batteries, one based on the thermo-electric effect which produces electricity directly from heat, outlined here, and the other based on chemical or galvanic reactions which is covered in a separate section on Thermal Batteries.

Based on the Seebeck effect, in a closed circuit made up from two dissimilar metals, an electrical potential is created between the two junction points when one junction is heated, usually by a gas burner, and the other kept cool. Since the late nineteenth century this technique has been used charge storage batteries and more recently to generate emergency power. The system is not energy efficient and is only suitable for low power applications. Modern gas powered batteries based on the Seebeck effect are still available today. They operate over a wide temperature range and are often used in conjunction with solar or wind powered batteries to provide remote or emergency power on dark, windless days.

History

Springs - The Clockwork Battery

Energy is stored in spring which is wound up by a clockwork mechanism. When released, the spring is used to drive a dynamo which provides the electrical power. This is suitable only for low capacity and low power applications and limited by the short duration of the discharge. The discharge period can however be extended by using suitable gearing. The Trevor Bayliss wind-up radio is an example of this method. His clockwork battery produced 3 volts at 55-60 milliwatts giving 40 minutes of play for 20 seconds of winding.

The energy stored in a linear spring is given by the following formula

$$\mathbf{E = \tfrac{1}{2} Kx^2}$$

Where **K** is the spring constant (force required per unit extension) and **x** is the extension of the spring.

History

Flywheels - The Kinetic Battery

Energy storage in a flywheel is as old as the potters wheel. Slow speed flywheels, combined with opportunity charging at bus stops have been used since the 1950s for public transport applications, however they are very bulky and very heavy and this has limited their adoption.

The energy stored in a flywheel id given by the following formula

$$\mathbf{E = \tfrac{1}{2} I\omega^2}$$

Where **I** is the moment of inertia of the flywheel (ability of an object to resist changes in its rotational velocity) and ω is its rotational velocity (radians/

second).

The moment of inertia is given by

$$I = kMr^2$$

Where **M** is the mass of the flywheel, **r** its radius and **k** is its inertial constant.

k depends on the shape of the rotating object. For a flywheel loaded at rim such as a bicycle wheel or hollow cylinder rotating on its axis, **k = 1**, for a solid disk of uniform thickness or a solid cylinder, **k = ½.**

Modern super flywheels store kinetic energy in a high speed rotating drum which forms the rotor of a motor generator. When surplus electrical energy is available it is used to speed up the drum. When the energy is needed the drum provides it by driving the generator. Modern high energy flywheels use composite rotors made with carbon-fiber materials. The rotors have a very high strength-to-density ratio, and rotate at speeds up to 100,000 rpm. in a vacuum chamber to minimize aerodynamic losses. The use of superconducting electromagnetic bearings can virtually eliminate energy losses through friction.

The magnitude of the engineering challenge should not be underestimated. A 1 foot diameter flywheel, one foot in length, weighing 23 pounds spinning at 100,000 rpm will store 3 kWh of energy. However at this rotational speed the surface speed at the rim of the flywheel will be 3570 mph. or 4.8 times the speed of sound and the centrifugal force on particles at the rim is equivalent to 1.7 million G. The tensile strength of material used for the flywheel rim must be over 500,000 psi to stop the rotor from flying apart.

Flywheels are preferred over conventional batteries in many aerospace applications because of the following benefits

Flywheel vs Battery Energy Storage

Energy Storage Characteristic	Resulting Benefits
5 to 10+ times greater specific energy	Lower mass
Long life (15 yr.) Unaffected by number of charge/discharge cycles	Reduced logistics, maintenance, life cycle costs and enhanced vehicle integration
85-95% round-trip efficiency	More usable power, lower thermal loads, compared with <70-80% for battery system
High charge/discharge rates & no taper charge required	Peak load capability, 5-10% smaller solar array
Deterministic state-of-charge	Improved operability
Inherent bus regulation and power shunt capability	Fewer regulators needed

Advanced flywheels are used for protecting against interruptions to the national electricity grid.
The flywheel provides power during period between the loss of utility supplied power and either the return of utility power or the start of a sufficient back-up power system (i.e., diesel generator). Flywheels can discharge at 100 kilowatts (kW) for 15 seconds and recharge immediately at the same rate, providing 1-30 seconds of ride-through time. Back-up generators are typically online within 5-20 seconds.

Flywheels have also been proposed as a power booster for electric vehicles. Speeds of 100,000 rpm have been used to achieve very high power densities, however containment of the high speed rotor in case of accident or mechanical failure would require a massive enclosure negating any power density advantages. The huge gyroscopic forces of these high speed flywheels are an added complication. Practicalities have so far prevented the large scale adoption of flywheels for portable applications.

History

Compressed air - The Pneumatic Battery

Compressed Air Energy Storage (CAES) uses pressurized air as the energy storage medium. An electric motor-driven compressor is used to pressurize the storage reservoir using off-peak energy and air is released from the reservoir through a turbine during on-peak hours to produce electrical energy. 1 m^3 of cavern space can store 5 kWh of energy and minimum pressures are about 1200 psi.
Ideal locations for large compressed air energy storage reservoirs are aquifers (water bearing rock formations), depleted oil and gas wells, conventional mines in hard rock, and hydraulically mined salt caverns. Facilities are sized in the range of several hundred megawatts. Air can be stored in pressurized tanks for small systems.

Small systems have also been used in demonstrator hybrid cars.

History

Pumped storage - The Hydraulic Battery

Pumped storage hydroelectricity is another, relatively simple method of storing and producing large amounts of electricity to supply high peak demands. At times of low electrical demand, excess electrical capacity is used to pump water into an elevated reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine, generating electricity . About 70% of the electrical energy used to pump the water into the elevated reservoir can be regained in this process. Some facilities use abandoned mines as the lower reservoir, but many use the natural height difference between two natural bodies of water or artificial reservoirs. Many pumped storage plants have been installed throughout the world. Dinorwig in Wales is an example generating 1320 MW of power.

History

Superconducting Magnetic Energy Storage (SMES) - The Magnetic Battery

Superconducting magnetic energy storage systems store energy in the field of a large magnetic coil with direct current flowing. It can be converted back to AC electric current as needed. Low temperature SMES cooled by liquid helium is commercially available. High temperature SMES cooled by liquid nitrogen is still in the development stage and may become a viable commercial energy storage source in the future.

SMES systems are large and generally used for short durations, such as utility switching events.

History

Radioisotope Thermoelectric Generators (RTG) - The Nuclear Battery

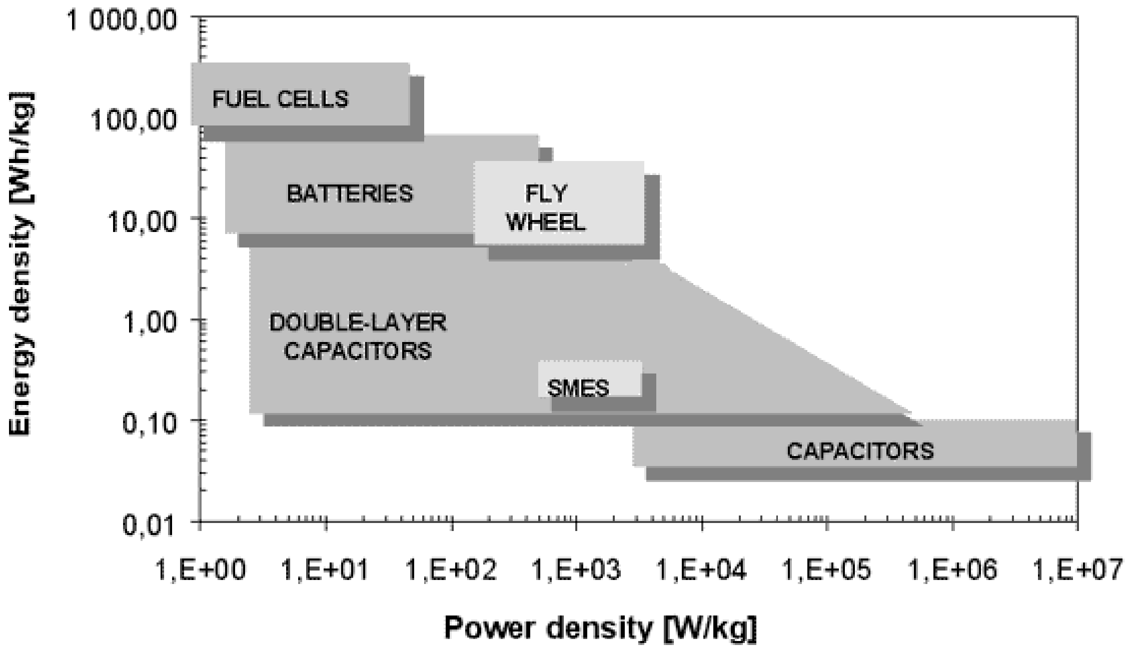
Radioisotope Thermoelectric Generators (RTGs) were designed for space applications and for providing power to remote installations such as lighthouses. Developed in 1959 by the Atomic Energy Commission at Los Alamos and introduced in 1961, these primary batteries are essentially nuclear powered heat generators which use energy emitted by the natural decay of radioactive isotopes of Plutonium (Pu-238) to provide the heat which in turn is used to generate electric power in a thermoelectric generator made from an array of thermocouples. Because the electric energy is created indirectly using the intermediate thermoelectric process the conversion efficiency is only about 4%, however the energy density of the radioactive source is thousands of times greater than Lithium Ion batteries. The technology provides long life batteries which never need recharging. Early batteries are still operational after over 25 years.

The direct conversion of nuclear energy into electricity is being developed for low power consumer applications. See **Betavoltaic Batteries**

History

Comparisons

The Ragone plot shows the energy storage and power handling capacity of some alternative storage techniques.



See more Ragone Plots in the Performance section

See also History 100 Battery Types

	Lead Acid	NiCad	NiMH	Zinc Air	Aluminium Air	Nickel Iron	Nickel Zinc	Sodium Sulphur	Zebra NaNiCl	$LiCoO_2$	$LiMn_2O_4$	Li-Ph	$LiNiCoO_2$	$LiNiO_2$	Li_2S_8	Lithium Metal	Lithium Metal
Commercialisation	1881	1956	1990	1997		1901	1920	1960	1982	1992	1999				2003	2002	2003
Cell Voltage	2.0 V	1.2V	1.2V	1.15V	1.5V	1.2V	1.5V	2.1V	2.58V	3.7V	3.6V	3.2V			2.1V	3.0V	4.0V
Energy by Weight: Wh/Kg	30-40	40-60	30-80	200	220	50	60	110	100	90-140	160	150			300	150	200
Specific Power W/Kg	180	150	250 - 1000	80-140	30	100	300	150	150	760	1800	???				250	
Energy by Volume Wh/L	60-75	50-150	140-300	220			100		160	220 –350	270	250			400		500
Max discharge rate	10C		20C							40C	40C						
Recharge Time	>10 Hours	8 Hours	6 Hours							< 3 Hours	< 3 Hours						
Cycle Life Cycles	500 -800	2000	1500	200			600	1000	1000	1200	1200						
Self Discharge per month	3% – 4%	20%	30%			20% - 40%	<20%		Zero	5% - 10%	5% - 10%				< 5%		
Temp Range °C		-40°C to +60°C	-20°C to +60°C							-20°C to +60°C	-20°C to +60°C						
Preferred Charge Method	Const Voltage	Const Current (- Delta V)	Dt/dt - (- Delta V) and Timer	NA	NA					Const Voltage Const Current	Const Voltage Const Current						
Average Energy Cost $/kWh	$150	$400-800	$250	$80		$150-200	$150-200		$300	$300	$300	$600 Target					
Comments Generally energy density depends on whether optimised for capacity or power	Deteriorates with microcycles	Memory Effect	High self discharge rate Useful power down to 50% DOD	Primary Cell Can not accept Regen loads Uses replacable electrodes	Primary Cell Can not accept Regen loads Needs booster due to low specific power	Corrosion problems	Dendrite growth causes short cycle life	High Temp 350°C Damaged if temp < 200°C Discontinued	High Temp 270°C	Expensive Toxic materials Useful power down to 80% DOD	Useful power down to 80% DOD	No field experience	No field experience	No field experience	No field experience	No field experience	No field experience

Electropaedia

Battery and Energy Technologies

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Battery Testing
Cell Chemistries
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History of Batteries (and other things)

Heroes and Villains - A little light reading

Here you will find a brief history of batteries, how they are made, and the applications they made possible, together with some interesting little known, or long forgotten, facts as well as a few myths about the development of the underlying technologies, the context in which they occurred and the deeds of the many personalities, eccentrics and charlatans involved.

"Either you do the work or you get the credit" Yakov Zel'dovich - Russian Astrophysicist

Fortunately it is not always true.

There's more to batteries than you might think. - Scroll down to see how it all happened.

You may find the **Search Engine**, the **Battery Timeline** or the **Hall of Fame** quicker if you are looking for something or somebody in particular.

Period?

See also the timeline of the **Discovery of the Elements**

Introduction

We think of a battery today as a source of portable power, but it is no exaggeration to say that the battery is one of the most important inventions in the history of mankind. Volta's pile was at first a technical curiosity but this new electrochemical phenomenon very quickly opened the door to new branches of both physics and chemistry and a myriad of discoveries, inventions and applications. The electronics, computers and communications industries, power engineering and much of the chemical industry of today were founded on discoveries made possible by the battery.

Pioneers

It is often overlooked that throughout the nineteenth century, most of the electrical experimenters, inventors and engineers who made these advances possible had to make their own batteries before they could start their investigations. They did not have the benefit of cheap, off the shelf, mass produced batteries. For many years the telegraph, and later the telephone, industries were the only consumers of batteries in modest volumes and it wasn't until the twentieth century that new applications created the demand that made the battery a commodity item.

In recent years batteries have changed out of all recognition. No longer are they simple electrochemical cells. Today the cells are components in battery systems, incorporating electronics and software, power management and control systems, monitoring and protection circuits, communications interfaces and thermal management.

2500 B.C. Sometimes known as the "Second oldest profession", **soldering** has been known since the Bronze Age (3500 to 1100 B.C.). A form of soldering to join sheets of gold was known to be used by the Chaldeans in Ur and also Mesopotamians (both in modern day Iraq). Fine metal working techniques were also developed in Egypt where filigree jewellery and cloisonné work found in **Tutankhamun**'s tomb dating from 1327 B. C. was made from delicate **wires** which had been drawn through **dies** and then soldered in place.

Egypt was also home to **Imhotep** the first man of science in recorded history. He was the world's first named architect and administrator who around 2725 B.C. built the first pyramid ever constructed, the Stepped Pyramid of Saqqara. Papyri were unearthed in the nineteenth century dating from around 1600 B.C. and 1534 B.C. both of which refer to earlier works attributed to Imhotep. The first outlines surgical treatments for various wounds and diseases and the second contains 877 prescriptions and recipes for treating a variety of medical conditions making Imhotep the world's first recorded physician. Other contemporary papyri described Egyptian mathematics. Egyptian teachings provided the foundation of Greek science and although Imhotep's teachings were known to the Greeks, 2200 years after his death, they assigned the honour of Father of Medicine to **Hippocrates**.

2300 B.C. The earliest evidence of the art of stenciling used by the Egyptians. Designs were cut into a sheet of papyrus and pigments were applied through the apertures with a brush. The technique was reputed to have been in use in **China** around the same time but no artifacts remain.

1300 B.C. Fine **wire** also made by the **Egyptians** by beating gold sheet and cutting it into strips. Recorded in the Bible, Book of Exodus, Chapter 39, Verse 3, - "And they did beat the gold into thin plates, and cut it into wires, to work it. in the fine linen, with cunning work."
The Egyptians also made coarse **glass fibres** as early as 1600 B.C. and fibers survive as decorations on Egyptian pottery dating back to 1375 B. C.

1280 B.C. Around this date, after his escape from Egypt, **Moses** ordered the construction of the **Ark of the Covenant** to house the tablets of stone on which were writen the original "Ten Commandments". Its construction is described in great detail in the book of Exodus and according to the Bible and Jewish legend it was endowed with miraculous powers including emitting sparks and fire and striking dead **Aaron**'s sons and others who touched it. It was basically a wooden box of acacia wood lined with gold and also overlaid on the outside with gold. The lid was decorated with two "cherubim" with outstretched wings. In 1915 Nikola **Tesla**, in an essay entitled "The Fairy Tale of Electricity" promoting the appreciation of electrical developments, proposed what seemed a plausible explanation for some of the magical powers of the Ark. He claimed that the gold sheaths separated by the dry acacia wood effectively formed a large capacitor on which a static electrical charge could be built up by friction from the curtains around the Ark and this accounted for the sparks and the electrocution of Aaron's sons.

Recent calculations have shown however that the capacitance of the box would be in the order of 200 picofarads and such a capacitor would need to be charged to 100,000 volts to store even 1 joule of electrical energy, not nearly enough to cause electrocution. It seems Tesla's explanation was appropriately named.

800 B.C. The **magnetic properties** of the naturally occurring lodestone were first mentioned in **Greek** texts. Also called **magnetite**, lodestone is a magnetic oxide of iron (Fe_3O_4) which was mined in the province of Magnesia in Thessaly from where the **magnet** gets its name. Lodestone was also known in China at that time where it was known as "love stone" and is in fact quite common throughout the world.
Surprisingly although they were aware of its magnetic properties, neither the Greeks nor the Romans seem to have discovered its directive

property.

Eight hundred years later in 77 A.D., the somewhat unscientific Roman chronicler of science **Pliny the Elder**, completed his celebrated series of books entitled "**Natural History**". In it he attributed the name "magnet" to the supposed discoverer of lodestone, the shepherd Magnes, "the nails of whose shoes and the tip of whose staff stuck fast in a magnetic field while he pastured his flocks". Thus another myth was born. Pliny was killed during the volcanic eruption of Mount Vesuvius near Pompeii in A.D. 79 but his "Natural History" lived on as an authority on scientific matters up to the Middle Ages.

600 B.C. The Greek philosopher and scientist, **Thales** of Miletus - one of the Seven Wise Men of Greece - demonstrated the effect of **static electricity** by picking up small items with an amber rod made of fossilised resin which had been rubbed with a cloth. He also noted that iron was attracted to **lodestone**.
Thales was the first thinker to attempt to explain natural phenomena by means of some underlying scientific principle rather than by attributing them to the whim of the Gods - a major departure from previous wisdom and the foundation of **scientific method**.
Thales left no writings - knowledge of him is derived from an account in **Aristotle**'s Metaphysics.

460 B.C. Another Greek philosopher **Democritus** of Abdera developed the idea that matter could be broken down into very small indivisible particles which he called **atoms**. Subsequently **Aristotle** dismissed Democtritus' **atomic theory** as worthless and Aristotle's views tended to prevail. It was not until 1803 that Democritus' theory was resurrected by John **Dalton**.

350 B.C. The Greek philosopher and scientist **Aristotle** (384-322 B.C.) provided "scientific" theories based on pure "**reason**" for everything from the structure of the cosmos down to the four fundamental **elements** earth, fire, air and water.

Aristotle believed that knowledge should be gained by pure thought and had no time for mathematics which he regarded only as a calculating device. Neither did he support the **experimental method** of scientific discovery which he considered inferior. In his support it should be mentioned that the range of experiments he could possibly undertake was limited by the lack of accurate measuring instruments in his time and it was only in the seventeenth century that instruments such as microscopes, telescopes, clocks with minute hands, accurate weighing equipment, thermometers and manometers started to become available.
Unfortunately Aristotle's "**rational**" explanations were subsequently taken up by **St Thomas Aquinas** (1225-1274) and espoused by the church which for many years made it difficult, if not dangerous, to propose alternative theories. Aristotle's theories of the cosmos and chemistry thus held sway for 2000 years hampering scientific progress until they were finally debunked by **Newton** and **Lavoisier** who showed that natural phenomena could be described by mathematical laws.
See also **Gilbert** (1600) and **Descartes** (1644)

Aristotle was also a tutor to the young **Alexander the Great**

250 B.C. The **Baghdad Battery** - In 1936 several unusual earthenware jars, dating from about 250 B.C., were unearthed during archeological excavations at Khujut Rabu near Baghdad. A typical jar was 130 mm (5-1/2 inches) high and contained a copper cylinder, the bottom of which was capped by a copper disk and sealed with bitumen or asphalt. An iron rod was suspended from an asphalt stopper at the top of the copper cylinder into the centre of the cylinder. The rod showed evidence of having been corroded with an acidic agent such as wine or vinegar. 250 BC corresponds to the Parthian occupation of **Mesopotamia** (modern day Iraq) and the the jars were held in Iraq's State Museum in Baghdad. In 1938 they were examined by German archeologist Wilhelm **König** who concluded that they were Galvanic cells or batteries supposedly used for gilding silver by electroplating. A mysterious anachronism. Backing up his claim, König also found copper vases plated with silver dating from earlier periods in the Baghdad Museum and other evidence of (electro?)plated articles from Egypt. Since then, several replica batteries have been made using various electrolytes including copper sulphate and grape juice generating voltages from half a Volt to over one Volt and they have successfully been used to demonstrate the electroplating of silver with gold. One further, more recent, suggestion by Paul T. Keyser a specialist in Neat Eastern Studies from the University of Alberta is that the galvanic cells were used for analgesia. There is evidence that electric eels had been used to numb an area of pain, but quite how that worked with such a low voltage battery is not explained. Apart from that, no other compelling explanation of the purpose of these artifacts has been proposed and the enigma still remains.

Despite warnings about the safety of these priceless articles before the 2003 invasion of Iraq, they were plundered from the museum during the war and their whereabouts is now unknown.

A nice and oft repeated story but there is a counter view about their purpose.
The **Parthians** were nomadic a nomadic tribe of skilled warriors and not noted for their scientific achievements. The importance of such an unusual electrical phenomenon seems to have gone completely unrecorded within the Parthian and contemporary cultures and then to have been completely forgotten despite extensive historical records from the period.
There are also some features about the artifacts themselves which do not support the battery theory. The asphalt completely covers the copper cylinder, electrically insulating it so that no current could be drawn without modifying the design and no wires, conductors, or any other sort of electrical equipment associated with the artifacts have been found. Furthermore the asphalt seal forms a perfect seal for preventing leakage of the electrolyte but it would be extremely inconvenient for a primary galvanic cell which would require frequent replacement of the electrolyte. As an alternative explanation for these objects, it has been noted that they resemble storage vessels for sacred scrolls. It would not be at all surprising if any papyrus or parchment inside had completely rotted away, perhaps leaving a trace of slightly acidic organic residue.

220-206 B.C. The **magnetic compass** was invented by the **Chinese** during the **Qin (Chin)** Dynasty, named after China's first emperor **Qin Shi Huang di**, the man who built the wall. It was used by imperial magicians mostly for **geomancy** (Feng Shui and fortune telling) but the "Mighty Qin's" military commanders were supposed to be the first to use a lodestone as a compass for navigation. Chinese compasses point south.

27 B.C. - 5th Century A.D. The Roman Empire. **The Romans** were great plumbers but poor electricians.
The Romans were deservedly renowned for their civil engineering - buildings, roads, bridges, aqueducts, central heating and baths. Surprisingly however, in 500 years, they didn't advance significantly on the legacies of mathematics and scientific theories left to them by **the Greeks**. Fortunately, the works of the Greek philosophers and mathematicians were preserved by **Arab scholars** who translated them into Arabic.

200 Greek philosopher Claudius **Galen** from Pergamum, Asia Minor, physician to five **Roman** emperors and surgeon to the Roman gladiators, was the first of many to claim therapeutic powers of magnets and to use them in his treatments.

426 Electric and magnetic phenomena were investigated by **St Augustine** who is said to have been "thunderstruck" on witnessing a magnet lift a chain of rings. In his book "City of God" he uses the example of magnetic phenomena to defend the idea of **miracles**. Magnetism could not be explained but it manifestly existed, so miracles should not be dismissed just because they could not be explained.

619 In 1999, archaeologists at Nendrum on Mahee Island in Ireland investigating what they thought to be a stone tidal pond used for catching fish uncovered two stone built **tidal mills** with a millstones and paddle blades dating from 619 AD and 787 AD. Several tidal mills were buillt during the Roman occupation of England for grinding grain and corn. They operated by storing water behind a dam during high tide, and letting it out to power the mill after the tide had receded and were the forerunners of the modern schemes for capturing **tidal energy**.

645 Xuan Zhuang the great apostle of Chinese Buddhism returned to China from India with Buddhist images and more than 650 Sanskrit Buddhist scriptures which were reproduced in large quantities giving impetus to the refinement of traditional methods of printing using **stencils** and **inked squeezes** first used by the **Egyptians**. A pattern of rows of tiny dots was made in a sheet of paper which was pressed down on top of a blank sheet and ink was forced through the holes. Later stencils developed by the Chinese and Japanese used human hair or silk thread to tie delicate isolated parts into the general pattern but there was no fabric backing to hold the whole image together. The stencil image was printed using a large soft brush, which did not damage the delicate paper pattern or the fine ties. These printing techniques of composite inked squeezes and stencils foreshadowed modern **silk screen printing** which was not patented until 1907.

700 - 1100 Islamic Science During **Roman times**, the flame of Greek science was maintained by Arab scholars who translated Greek scientific works into Arabic. From 700 A.D. however, when most of Europe was still in the Dark Ages, scientific developments were carried forward on a broad front by the Muslim world with advances in astronomy, mathematics, physics, chemistry and medicine. **Chemistry** (Arabic Al Khimiya "pour together", "weld") was indeed the invention of the Muslims who carried out pioneering work over three centuries putting chemistry to practical uses in the refinement of metals, dyeing, glass making and medicine. In those days the notion of **alchemy** also included what we would today call chemistry. Among the many notable muslim scientists from this period were **Jabir Ibn Haiyan**, **Al-Khawarizmi** and **Al-Razi**.

By the tenth century however, according to historian Toby **Huff**, the preeminence of Islamic science began to wane. It had flourished in the previous three centuries while Muslims were in the minority in the Islamic regions however, starting in the tenth century, widespread conversion to Islam took place and as the influence of Islam increased, so the tolerance of alternative educational and professional institutions and the radical ideas of freethinkers decreased. They were dealt a further blow in 1485, thirty five years after the invention of the **printing press**, when the Ottoman **Sultan Byazid II** issued an order forbidding the printing of Arabic letters by machines. Arabic texts had to be translated into Latin for publication and this no doubt hampered both the spread of Islamic science and ideas as well as the influence of the outside world on the Islamic community. This prohibition of printing was strictly enforced by subsequent Ottoman rulers until 1728 when the first printing press was established in Istanbul but due to objections on religious grounds it closed down in 1742 and the first Koran was not printed in Istanbul until 1875. Meanwhile in

1734 Deacon **Abdalla Zakhir** of the Greek Catholic Maronite Monastery of Saint John Sabigh in the Lebanon managed to establish the first independent Arabic printing press.

Islam was not alone in banning the dissemination of subversive or inconvenient ideas. **Henry VIII** in 1529, aware of the power of the press, became the first monarch to publish a list of banned books though he did not go so far as banning printing. He was later joined by others. In 1632 Galileo's book "Dialogue Concerning the Two Chief World Systems", in which he asserted that the earth revolved around the sun rather than the other way round, was placed by **Pope Urban VIII** on the index of banned books and Galileo was placed under house arrest. Despite these setbacks, European scientific institutions overcame the challenges by the church, taking over the flame carried by the Arabs and the sixteenth and seventeenth centuries became the age of **Scientific Revolution** in Europe.

776 Persian chemist Abu Musa **Jabir Ibn Haiyan** (721-815), also known as **Geber**, was the first to put chemistry on a scientific footing, laying great emphasis on the importance of formal experimentation. In the period around 776 A.D. he perfected the techniques of crystallisation, distillation, calcination, sublimation and evaporation and developed several instruments including the **alembic** (Arabic al-ambiq, "still") which simplified the process of distillation, for carrying them out. He isolated or prepared several chemical compounds for the first time, notably nitric, hydrochloric, citric and tartaric **acids** and published a series of books describing his work which were used as classic works on alchemy until the fourteenth century. Unfortunately the books were added to, under Geber's name, by various translators in the intervening period leading to some confusion about the extent of Geber's original work.

830 Around the year 830, Baghdad born mathematician Mohammad Bin Musa **Al-Khawarizmi** (770-840) published "The Compendium Book on Calculation by Completion and Balancing" in which he introduced the principles of **algebra** (Arabic Al-jabr "the reduction" i.e. of complicated relationships to a simpler language of symbols) which he developed for solving linear and quadratic equations. He also introduced the decimal system of Hindu-Arabic numerals to Europe as well as the concept of **zero**, a mathematical device at the time unknown in Europe used to Roman numerals. Al-Khawarizmi also constructed **trigonometric tables** for calculating the sine functions. The word **algorithm** (algorizm) is named after him.

920 Around the year 920, Persian chemist Mohammad Ibn Zakariya **Al-Razi** (865-925), known in the West as **Rhazes**, carried on Geber's work and prepared **sulphuric acid**, the "work horse" of modern chemistry and a vital component in the world's most common battery. He also prepared ethanol, which was used for medicinal applications, and described how to prepare **alkali** (Al-Qali, the salt work ashes, potash) from oak ashes. Al-Razi published his work on alchemy in his "Book of Secrets". The precise amounts of the substances he specified in his recipes demonstrates an understanding of what we would now call stoichiometry.

Several more words for chemicals are derived from their Arabic roots including **alcohol** (Al Kuhl" "essence", usually referring to ethanol) as well as arsenic and borax.

1000

1040 Thermoremanent magnetisation described in the **Wu Ching Tsung Yao** "Compendium of Military Technology" in China. Compass needles were made by heating a thin piece of iron, often in the shape of a fish, to a temperature above the **Curie Point** then cooling it in line with the earth's magnetic field.

1041 Between 1041 and 1048 Chinese craftsman **Pi Sheng** produced the first **printing press** to use **moveable type**. Although his designs achieved widespread use in China, it was another four hundred years before the printing press was "invented" by Johann **Gutenberg** in Europe.

1086 Chinese astronomer, cartographer and mathematician **Shen Kua**, in his Dream Pool Essays, describes the **compass** and its use for navigation and cartography as well as **Pi Sheng**'s printing technique.

1190 The **magnetic compass** "invented" in Europe 1400 years after the Chinese. Described for the first time in the west by a St Albans monk Alexander **Neckam** in his treatise De Naturis Rerum.

1250's Italian theologian **St Thomas Aquinas** stands up for the cause of "**reason**" reconciling the philosophy of **Aristotle** with **Christian doctrine**. Challenging Aristotle now became a challenge to the Church.

1269 Petrus Peregrinus de Marincourt, (Peter the Pilgrim) a French Crusader, used a compass to map the magnetic field of a lodestone. He discovered that a magnet had two **magnetic poles**, North and South and was the first to describe the phenomena of attraction and repulsion. He also speculated that these forces could be harnessed in a machine.

1368-1644 China's Ming dynasty. When the Ming dynasty came into power, China was the most advanced nation on earth. During the Dark Ages in Europe, China had developed the **compass**, gunpowder, paper, paper money, canals and locks, block printing, moveable type, porcelain, pasta and many other inventions centuries before they were "invented" by the Europeans. They were so far ahead of Europe that when **Marco Polo** described these wondrous inventions in 1295 on his return to Venice from China he was branded a liar. China's innovation was based on practical inventions founded on empirical studies, but their inventiveness seems to have deserted them during the Ming dynasty and subsequently during the **Qing (Ching) dynasty** (1644 - 1911). China never developed a theoretical science base and the industrial revolution passed China by. Why should this be?

It is said that the answer lies in Chinese culture, to some extent **Confucianism** but particularly **Daoism (Taoism)** whose teachings promoted **harmony with nature** whereas Western aspirations were the **control of nature**. However these conditions existed before the Ming when China's innovation led the world. A more likely explanation can be found in China's imperial political system in which a massive society was rigidly controlled by all-powerful emperors through a relatively small cadre of professional administrators (Mandarins) whose qualifications were narrowly based on their knowledge of Confucian ideals. If the emperor was interested in something, it happened, if he wasn't, it didn't happen.
The turning point in China's technological dominance came when the Ming emperor **Xuande** came to power in 1426. Admiral **Zheng He**, a muslim eunuch, castrated as a boy when the Chinese conquered his tribe, had recently completed an audacious voyage of exploration on behalf of a previous Ming emperor **Yongle** to assert China's control of all of the known world and to extract tributary from its intended subjects. But his new

master considered the benefits did not justify the huge expense of Zheng's fleet of 62 enormous nine masted junks and 225 smaller supply ships with their 27,000 crew. The emperor mothballed the fleet and henceforth forbade the construction of any ships with more than two masts, curbing China's aspirations as a maritime power and putting an end to its expansionist goals, a xenophobic policy which has lasted until current times.
The result was that during both the Ming and the Qing dynasties a succession of complacent, conservative emperors cocooned in prodigious, obscene wealth, remote even from their own subjects, lived in complete isolation and ignorance of the rest of the world. Foreign influences, new ideas, and an independent merchant class who sponsored them, threatened their power and were consequently suppressed. By contrast the West was populated by smaller, diverse and independent nations competing with eachother. Merchant classes were encouraged and innovation flourished as each struggled to gain competitive or military advantage.

Times have changed. Currently China is producing two million graduates per year, sixty percent of which are in science and technology subjects, three times as many as in the USA.
After Japan, China is the second largest battery producer in the world and growing fast.

1450 German goldsmith and calligrapher Johann Genstleisch zum **Gutenberg** from Mainz invented the **printing press**, considered to be one of the most important inventions in human history. For the first time knowledge and ideas could be recorded and disseminated to a much wider public than had previously been possible using hand written texts and its use spread rapidly throughout Europe. Intellectual life was no longer the exclusive domain of the church and the court and an era of enlightenment was ushered in with science, literature, religious and political texts becoming available to the masses who in turn had the facility to publish their own views challenging the status quo. Nowadays the **Internet** is bringing about a similar revolution.

Although it was new to Europe, the Chinese had already invented printing with **moveable type** four hundred years earlier but, because of China's isolation, these developments never reached Europe.

Gutenberg printed Bibles and supported himself by printing indulgences, slips of paper sold by the Catholic Church to secure remission of the temporal punishments in Purgatory for sins committed in this life. He was a poor businessman and made little money from his printing system and depended on subsidies from the Archbishop of Mainz. Because he spent what little money he had on alcohol, the Archbishop arranged for him to be paid in food and lodging, instead of cash. Gutenberg died penniless in 1468.

1474 The first **patent law**, a statute issued by the **Republic of Venice**, provided for the grant of exclusive rights for limited periods to the makers of inventions. It was a law designed more to protect the economy of the state than the rights of the inventor since, as the result of its declining naval power, Venice was changing its focus from trading to manufacturing. The Republic required to be informed of all new and inventive devices, once they had been put into practice, so that they could take action against potential infringers.

1499 The first **patent** for an invention was granted by **King Henry VI** to Flemish-born **John of Utynam** for a method of making stained glass, required for the windows of Eton College giving John a 20-year monopoly. The Crown thus started making specific grants of privilege to favoured manufacturers and traders, signified by **Letters Patent**, open letters marked with the King's Great Seal.

The system was open to corruption and in 1623 the **Statute of Monopolies** was enacted to curb these abuses. It was a fundamental change to patent law which took away the rights of the Crown to create trading monopolies and guaranteed the inventor the legal right of patents instead of depending on the royal prerogative. So called **patent law**, or more generally **intellectual property law**, has undergone many changes since then to encompass new concepts such as copyrights and trademarks and is still evolving as and new technologies such as software and genetics demand new rules.

1515 Leonardo da Vinci proposed the use of a large concave mirror to capture **solar energy** to heat water in a boiler used in a dye works.

1593 The **thermometer** invented by Italian astronomer and physicist **Galileo** Galilei. It has been variously called an air thermometer or a water thermometer but it was called a **thermoscope** at the time. His "thermometer" consisted of a glass bulb at the end of a long glass tube held vertically with the open end immersed in a vessel of water. As the temperature changed the water would rise or fall in the tube due to the contraction or expansion of the air. It was sensitive to air pressure and could only be used to indicate temperature changes since it had no scale. In 1612 Italian Santorio **Santorio** added a scale to the apparatus creating the first true thermometer and for the first time, temperatures could be quantified.

There is no evidence that the decorative, so called, **Galileo thermometers** based on the Archimedes principle were invented by Galileo or that he ever saw one. They are comprised of several sealed glass floats in a sealed liquid filled glass cylinder. The density of the liquid varies with the temperature and the floats are designed with different densities so as to float or sink at different temperatures. There were however thriving glass blowing and thermometer crafts based in Florence (Tuscany) where the Academia del Cimento, which was noted for its instrument making, produced many of these thermometers also known as **Florentine thermometers** or **Infingardi** (Lazy-Ones) or **Termometros Lentos** (Slow) because of the slowness of the motion of the small floating spheres in the alcohol of the vial. It is quite likely that these designs were the work of the Grand Duke of Tuscany **Ferdinand II** who had a special interest in thermometers and meteorology.

1600 William **Gilbert** of Colchester, physician to Queen Elizabeth I of England published "**De Magnete**" (On the Magnet) the first ever work of experimental physics. In it he distinguished for the first time **static electric forces** from **magnetic forces**. He discovered that the earth is a giant magnet just like one of the stones of **Peregrinus**, explaining how compasses work. He is credited with coining the word "**electric**" which comes from the Greek word "**elektron**" meaning amber.

Many wondrous powers have been ascribed to magnets and to this day magnetic bracelets are believed by some to have therapeutic benefits. In Gilbert's time it was believed that an adulteress could be identified by placing a magnet under her pillow. This would cause her to scream or be thrown out of bed as she slept.
Gilbert proved amongst other things that the smell of garlic did not affect a ship's compass. It is not known whether he experimented with adulteresses in his bed.

Gilbert was the English champion of the **experimental method** of scientific discovery considered inferior to **rational thought** by the Greek philosopher **Aristotle** and his followers. He held the Copernican view, dangerous at the time, that the world was not the centre of the universe. He was a contemporary of the more famous Italian astronomer Galileo Galilei (1564-1642) who made a principled stand in defence of the founding of physics on scientific method and precise measurements rather than on metaphysical principles and formal logic. These views brought Galileo into serious confrontation with the church and he was tried and punished for his heresies.

Gilbert died of Bubonic plague in 1603 leaving his books, globes, instruments and minerals to the College of Physicians but they were destroyed in 1666 in the great fire of London which mercifully also brought the plague to an end.

1603 Italian shoemaker and part-time alchemist from Bologna, Vincenzo **Cascariolo**, searching for the "**Philosopher's Stone**" for turning common metals into Gold discovered **phosphorescence** instead. He heated a mixture of powdered coal and heavy spar (Barium sulphate) and spread it over an iron bar. It did not turn into Gold when it cooled, as expected, but he was astonished to see it glow in the dark. Though the glow faded it could be "reanimated" by exposing it to the sun and so became known as "lapis solaris" or "sun stone", a primitive method of **solar energy storage** in chemical form.

1605 A five digit **encryption** code consisting only of the letters "a" and "b" giving 32 combinations to represent the letters of the alphabet was devised by English philosopher and lawyer Francis **Bacon**. He called it a **biliteral code**. It is directly equivalent to the five bit binary Baudot code of ones and zeros used for over 100 years for transmitting data in twentieth century telegraphic communications.
More importantly Bacon, together with **Gilbert**, was an early champion of scientific method although it is not known whether they ever met.

Bacon died as a result of one of his experiments. He investigated preserving meat by stuffing a chicken with snow. The experiment was a success but Bacon died of bronchitis contracted either from the cold chicken or from the damp bed, reserved for VIP's and unused for a year, where he was sent to recover from his chill.

There are many "Baconians" who claim today that at least some of **Shakespeare**'s plays were actually written by Bacon. One of the many arguments put forward is that only Bacon possessed the necessary wide range of knowledge and erudition displayed in Shakespeare's plays.

1629 Italian Jesuit priest Nicolo **Cabeo** published Philosophia Magnetica in which **electric repulsion** is identified for the first time.

1643 Evangelista **Torricelli** served as Galileo's secretary and succeeded him as court mathematician to Grand Duke Ferdinand II and in 1643 made the world's first **barometer** for measuring atmospheric pressure by balancing the pressure force, due to the weight of the atmosphere, against the weight of a column of mercury.

1644 French philosopher and mathematician René **Descartes** published **Principia Philosophiae** in which he attempts to put the whole universe on a mathematical foundation reducing the study to one of mechanics. Considered to be the first of the modern school of mathematics, he believed that Aristotle's logic was an unsatisfactory means of acquiring knowledge and that only mathematics provided the truth so that all reason must be based on mathematics.
His most important work **La Géométrie**, published in 1637, includes his application of algebra to geometry from which we now have **Cartesian geometry**.

Descartes accepted sponsorship by **Queen Christina of Sweden** who persuaded him to go to Stockholm. Her daily routine started at 5.00 a.m. whereas Descartes was used to rising at at 11 o'clock. After only a few months in the cold northern climate, walking to the palace for 5 o'clock every morning, he died of pneumonia.

1646 The word **Electricity** coined by English physician Robert **Browne** even though he contributed nothing else to the science.

1650

1651 German chemist Johann Rudolf **Glauber** in his "Practise on Philosophical Furnaces" describes a **safety valve** for use on chemical retorts. It consisted of a conical valve with a lead cap which would lift in response to excessive pressure in the retort allowing vapour to escape and the pressure to fall. The weight of the cap would reseat the valve once the pressure returned to an acceptable level. Today, modern implementations of Glauber's valve are the basis of the **pressure vents** incorporated into **sealed batteries** to prevent rupture of the cells due to pressure build up. In 1658 Glauber published **Opera Omnia Chymica** "Complete Works of Chemistry", a description of different techniques for use in chemistry which was widely reprinted.

1654 The first **sealed liquid-in-glass thermometer** produced by the artisan **Mariani** at the Accademia del Cimento in Florence for the Grand Duke of Tuscany, **Ferdinand II**. It used alcohol as the expanding liquid but was inaccurate in absolute terms, although his thermometers agreed with eachother, and there was no standardised scale in use.

1661 Dutch physicist and astronomer Christiaan **Huygens** invents the **U tube manometer**, a modification of **Torricelli's barometer**, for determining gas pressure differences. In a typical "U Tube" manometer the difference in pressure (really a difference in force) between the ends of the tube is balanced against the weight of a column of liquid. The gauges are only suitable for measuring low pressures, most gauges recording the difference between the fluid pressure and the local atmospheric pressure when one end of the tube is open to the atmosphere.

1661 Irish chemist Robert **Boyle** published **"The Sceptical Chymist"** in which he introduced the concept of **elements**. At the time only 12 elements had been identified. These included nine metals, Gold, Silver, Copper, Tin, Lead, Zinc, Iron, Antimony and Mercury and two non metals Carbon and Sulphur all of which had been known since antiquity as well as Bismuth which had been discovered in Germany around 1400 A.D.. Platinum had been known to South American Indians from ancient times but only became to the attention of Europeans in the eighteenth century. Boyle himself discovered phosphorus which he extracted from urine in 1680 taking the total of known elements to fourteen.
Though an **alchemist** himself, believing in the possibility of transmutation of metals, he was one of the first to break with the alchemist's tradition of secrecy and published the details of his experimental work including failed experiments.

1662 Boyle published **Boyle's Law** stating that the pressure and volume of a gas are inversely proportional.
PV=K The first of the **Gas Laws**.
The relationship was also discovered by the French physicist Edme **Mariotte** in 1676 and is known by his name in non-English speaking countries.

1663 Otto **van Guericke** the Burgomaster of Magdeburg in Germany invented the first **electric generator**, which produced static electricity by rubbing a pad against a large rotating sulphur ball. The first machine to produce an electric spark and remained the standard way of producing electricity for over a century. Van Guericke was famed for his studies of the properties of a vacuum and for his design of the Magdeburg Hemispheres experiment.

1665 **Boyle** published a description of a **hydrometer** for measuring the density of liquids which was essentially the same as those still in use today for measuring the **specific gravity (S.G.)** of the electrolyte in Lead Acid batteries. Hydrometers consist of a sealed capsule of lead or mercury inside a glass tube into which the liquid being measured is placed. The height at which the capsule floats represents the density of the liquid.
The hydrometer, called the **aerometer** by the Greeks, is however considered to be the invention of **Hypatia** head of the Platonist school at Alexandria in about 400 A.D. where she lectured on mathematics and philosophy. Unfortunately she was killed by a Christian mob who at the time equated science with paganism.

1675 **Boyle** discovered that **electric force** could be transmitted through a vacuum and observed **attraction** and **repulsion**.

1676 Prolific English engineer, surveyor, architect, physicist, inventor, socialite and self publicist, Robert **Hooke**, is now mostly remembered for for **Hooke's Law** for springs which states that the extension of a spring is proportional to the force applied, or as he wrote it in Latin "**Ut tensio, sic vis**" ("as is the extension, so is the force"). From this the energy stored in the spring can be calculated by integrating the force times the displacement over the extension of the spring. The force per unit extension is known as the **spring constant**. Hooke actually discovered his law in 1660, but afraid that he would be scooped by his rival **Newton**, he published his preliminary ideas as an anagram "**ceiiinosssttuv**" in order to register his claim for priority. It was not until 1676 that he revealed the law itself. The forerunner of digital **time stamping**?

Hooke was surveyor of the City of London and assistant to Christopher Wren in rebuilding the city after the great fire of 1666. He made valuable contributions to optics, microscopy, astronomy, the design of clocks, the theories of springs and gases, the classification of fossils, meteorology, navigation, music, mechanical theory and inventions, but despite his many achievements he was overshadowed by his contemporary Newton with whom he was unfortunately, constantly in dispute. Hooke claimed a role in some of Newton's discoveries but he was never able to back up his theories with mathematical proofs. Apparently there was at least one subject which he had not mastered.

1679 German mathematician, diplomat and philosopher Gottfried Wilhelm **Leibniz** introduced **binary arithmetic** in a letter written to French mathematician and Jesuit missionary to China, Joachim **Bouvet**, showing that any number may be expressed by 0's and 1's only. Now the basis of digital logic and signal processing used in computers and communications.
Surprisingly Leibniz also suggested that God may be represented by unity, and "nothing" by zero, and that God created everything from nothing. He was convinced that the logic of Christianity would help to convert the Chinese to the Christian faith. He believed that he had found an historical precedent for this view in the 64 hexagrams of the Chinese **I Ching** or the **Book of Changes** attributed to China's first shaman-king **Fuxi** (Fu Hsi) dating from around 2800 B.C. and first written down as the now lost manual Zhou Yi in 900 B.C.. A hexagram consists of blocks of six solid or broken lines (or stalks of the Yarrow plant) forming a total of 64 possibilities. The solid lines represent the bright, positive, strong, masculine **Yang** with active power while the broken or divided lines represent the dark, negative, weak, feminine **Yin** with passive power. According to the I Ching,

the two energies or polarities of the Yin and Yang are both opposing and complementary to eachother and represent all things in the universe which is a progression of contradicting dualities.
Although the I Ching had more to do with fortune telling than with mathematics, there were other precedents to Leibniz's work. The first known description of a binary numeral system was made by Indian mathematician **Pingala** variously dated between the 5th century B.C. or the 2nd century B.C..

Between the years 1673 and 1686 Leibniz developed the his theories of mathematical calculus publishing the first account of **differential calculus** in 1684 followed by the explanation of **integral calculus** in 1686. Unknown to him these techniques were also being developed independently by **Newton** and arguments about priority raged for many years after both men published their works. Leibniz's notation has been adopted in preference to Newton's but the concepts are the same.

Leibniz also introduced the words **function, variable, constant, parameter** and **coordinates** to explain his techniques.
His most famous philosophical proposition was that God created "**the best of all possible worlds**".

1681 French physicist and inventor Denis **Papin** invented the **pressure release valve** or **safety valve** to prevent explosions in pressure vessels. Although Papin is credited with the invention, safety valves had in fact been described by **Glauber** thirty years earlier, however Papin's valve was adjustable for different pressures by means of moving the lead weight along a lever which kept the valve shut. The invention of the safety valve came as a result of his work with pressurised steam. In 1679 he had invented the **pressure cooker** which he called the steam digester. Observing that the steam tended to lift the lid of his cooker in 1690 he conceived the idea of using the pressure of steam to drive a piston in a cylinder to perform a pumping action, the genesis of the **steam engine**. In 1707 Papin used his safety valve as a regulating device on a steam engine which he had built. Thereafter, it became a standard feature on steam engines saving many lives from explosions.

1687 "Philosophiae Naturalis Principia Mathematica" - **Mathematical Principles of Natural Philosophy** published by English physicist and mathematician Isaac **Newton**. One of the most important and influential books ever published, it was written in Latin and not translated into English until 1729.

By coincidence Newton was born in 1642, the year that Galileo died.
He made significant advances in the study of **Optics** demonstrating that white light is made up from the spectrum of colours observed in the rainbow. He used a prism to separate white light into its constituent colour spectrum and by means od a second prism he showed that the colours could be recombined into white light.
He is perhaps best remembered however for his **Mechanics**, the **Laws of Motion and Gravitation** which his "Principia" contains. The concept of **gravity** was completely new. Before that, planetary motion had been explained by **Gilbert** as well as his contemporary the German astronomer **Kepler** (1571-1630), and others as being due to magnetic forces.
Newton's first law of motion that "every body remains in a state of rest or uniform motion in a straight line unless compelled to change by some external force" is however a restatement of **Galileo**'s concept of **inertia** or resistance to change which is measured by its **mass**.

The impact of the publication of Newton's laws of dynamics on the scientific community was both profound and wide ranging. The laws and Newton's methods provided the basis on which other theories, such as **fluid dynamics**, **kinetic energy** and **work done** were built and down to earth technical knowledge which enabled the building of the machines to power the Industrial Revolution and, at the other end of the spectrum, they explained the workings of the Universe.

However, of equal or even greater importance was the fact that Newton showed for the first time, the general principle that natural phenomena, events and time varying processes, not just mechanical motions, obey laws that can be represented by mathematical equations enabling analysis and predictions to be made. The laws of nature represented by the laws of mathematics, the foundation of modern science. The 3 volume publication was thus a major turning point in the development of scientific thought, sweeping away superstition and so called "rational deduction" as ways of explaining the wonders of nature. Newton's reasoning was supported by his invention of the mathematical techniques of **Differential and Integral Calculus** and **Differential Equations**, actually developed in 1665 and 1666, twenty years before he wrote the "Principia" but not used in the proofs it contains. These were major advances in scientific knowledge and capability which extended the range of existing mathematical tools available for characterising nature and for carrying out scientific analysis.

Newton engaged in a prolonged feud with Robert **Hooke** who claimed priority on some of Newton's ideas. Newton's oft repeated quotation "If I have seen further, it is by standing on the shoulders of giants." was actually written in a sarcastic letter to Hooke, who was almost short enough to be classified as a dwarf, with the implication that Hooke didn't qualify as one of the giants.

Leibniz working contemporaneously with Newton also developed techniques of differential and integral calculus and a dispute developed with Newton as to who was the true originator. Newton's discovery was made first, but Leibniz published his work before Newton. However there is no doubt that both men came to the ideas independently. Newton developed his concept through a study of tangents to a curve and also considered variables changing with time, while Leibniz arrived at his conclusions from calculations of the areas under curves and thought of variables x, y as ranging over sequences of infinitely close values.

Newton is revered as the founder of modern physical science, but despite the great fame he achieved in his lifetime, he remained a modest, diffident, private and religious man of simple tastes. He never married, devoting his life to science.

Newton didn't always have his head in the clouds. In his spare time, when he wasn't dodging apples, he invented the **cat-flap**.

1700

1705 English physicist and instrument maker Francis **Hauksbee** the Elder demonstrated an **electroluminescent glow discharge lamp** which gave off enough light to read by. It was based on van Guericke's electric generator with an evacuated glass globe, containing mercury, replacing the sulphur ball. It produced a glow when he rubbed the spinning globe with his bare hands.

1713 Prolific French scientist and entomologist René-Antoine Ferchault de **Réaumur** invents **spun glass fibres**. In an attempt to make artificial feathers from glass he made fibres by rotating a wheel through a pool of molten glass, pulling out threads of glass where the hot, thick liquid stuck

to the wheel. His fibers were short and fragile, but he predicted that spun glass fibers as thin as spider silk would be flexible and could be woven into fabric.
In 1731 Réaumur also invented an alcohol thermometer and a corresponding **temperature scale** which both bear his name. The temperature scale assigned zero degrees to the freezing point of water and eighty degrees its boiling point. The freezing point was fixed and the tube graduated into degrees each of which was one-thousandth of the volume contained by the bulb and tube up to the zero mark. It was an accident dependent on the expansion of the particular quality of alcohol employed which made the boiling point of water 80 degrees.

1714 The first **mercury thermometer** was made by Polish inventor Gabriel **Fahrenheit**. It had improved accuracy over the **alcohol thermometer** due to the more predictable expansion of mercury combined with improved glassworking techniques. At the same time Fahrenheit introduced a standard **temperature scale** based on the two fixed points of the freezing and boiling points of water.

1725 French weaver Basile **Bouchon** used a **perforated paper roll** in a weaving loom to establish the pattern to be reproduced in the cloth. The world's first use of **manufacturing automation** by using a **stored program** to control an **automated machine**.

1728 Another French weaver, Jean **Falcon** worked with **Bouchon** to improve his design by changing the perforated paper roll to a chain of more robust **punched cards** to enable the program to be changed more quickly.

1729 English chemist Stephen **Gray** was the first to identify the phenomenon of **electric conduction** and the properties of **conductors** and **insulators** and the first to **transmit electricity** over a wire. He sent charges nearly 300 feet over brass wire and moistened thread and showed that electricity doesn't have to be made in place by rubbing but can also be transferred from place to place with **conducting** wire. An **electrostatic generator** powered his experiments, one charge at a time. The fore-runner to the **electric telegraph**.

1733 French soldier, diplomat and chemist Charles-Francois de Cisternay **du Fay** discovered two types of **electrical charge, positive** and **negative** which he called "vitreous" and "resinous" from the materials used to generate the charge.

1738 Swiss mathematician **Daniel Bernoulli** showed that **Newtons Laws** apply to fluids as well as solids and that as the velocity of a fluid increases, the pressure decreases, a statement known as the Bernoulli principle.
More generally the Bernoulli Equation is a statement of the conservation of energy in a form useful for solving problems involving **fluid mechanics** or fluid flow. For a non-viscous, incompressible fluid in steady flow, the sum of pressure, potential and kinetic energies per unit volume is constant at any point.
Bernoulli's equation also underpins the **theory of flight**. Lift is created because air passing over the top of the wing must travel further and hence faster that air travelling the shorter distance under the wing. This results in a lower pressure above the wing than below the wing and this pressure difference creates the lift.

Daniel Bernoulli was also the first to explain that the pressure exerted by a gas on the walls of its container is the sum of the many collisions by individual molecules, all moving independently of each other - the basis of the **gas laws** and the modern **kinetic theory of gases**.

Daniel Bernoulli was a member of a family of Bernoullis many of whom gained international distinction in mathematics. They were Calvinists of Dutch origin but were driven from Holland by religious persecution finally settling at Basel in Switzerland.

James (Jacques/Jakob) Bernoulli was the first to come to prominence. He learned about **calculus** from **Leibniz** and was one of the first users and promoters of the technique. In his **Ars Conjectandi**, "The Conjectural Arts" published in 1713, eight years after his death by his nephew **Nicholas Bernoulli**, he established the principles of the calculus of probabilities - the foundation of **probability theory** as well as the principles of **permutations and combinations**. He was also one of the first to use **polar coordinates**.

John (Jean/Johann) Bernoulli, James' brother and father of Daniel was clever but unscrupulous, fraudulently substituting the work of his brother James, of whom he was jealous, for his own to cover up his errors. He also banished his son Daniel from his home when he was awarded an prize he himself had expected to win. Nevertheless he was a great teacher an advanced the theory of calculus to explore the properties of **exponential** and other functions.

John's three sons Nicholas, Daniel and **John Bernoulli the younger** and his two sons John and James all achieved distinction in mathematics in their own right.

1744 Prolific French inventor Jacques **de Vaucanson** maker of **robot devices** and **automatons** playing musical instruments and imitating the movements of birds and animals, turned his attention to the problems of mechanisation of silk weaving. Building on the inventions of **Bouchon** and **Falcon**, he built a fully automated loom which used perforated cards to control the weaving of patterns in the cloth. Vaucanson also invented many machine tools and collected others which became the foundation of the 1794 Conservatoire des Arts et Métiers (Conservatory of Arts and Trades) collection in Paris. Although Vaucanson's loom was ignored during his lifetime, it was rediscovered more than a half century later at the Conservatoire by **Jacquard** who used it as the basis for his own improved design.

1745 Electricity first stored in a bottle (literally). The discovery of the **Leyden Jar**, essentially a large **capacitor**, was claimed by various experimenters but generally attributed to a Dutch physicist and mathematician Pieter van **Musschenbroek** and his student Andreas **Cunaeus** (whom he almost electrocuted with it) working at Leyden in Holland. The first source of **stored electrical energy** the Leyden jar was simply a jar filled with water, with metal foil around the outside and a nail piercing the stopper and dipping into the water.
A similar device was also invented at the same time by Ewald Jurgens **von Kleist** Dean of the Cathedral of Kammin in Germany.
The design was improved in 1747 by English astronomer John **Bevis** who replaced the water with an inner metal coating covering the bottom and sides nearly to the neck. A brass rod terminating in an external knob passed through a wooden stopper or cork and was connected to the inner coating by a loose chain or wire.

Until the advent of the battery, Leyden jars and electrostatic generators were the experimenters' only source of electrical energy. They were however not only made for scientific research, but also as curiosities for amusement. In the 18th century, everybody who had heard of it wanted to experience an electric shock. Experiments like the "electric kiss" were a salon pastime.

1746 French clergyman and physicist Jean Antoine **Nollet** demonstrated that electricity could be transmitted instantaneously over great distances suggesting that **communications** could be sent by electricity much faster than a human messenger could carry them.
With the connivance of the Abbot of the Grand Convent of the Carthusians in Paris he assembled 200 monks in a long snaking line with each monk holding the ends of eight metre long wires to form a chain about one mile long. Without warning he connected a **Leyden Jar** to the ends of the line giving the unsuspecting monks a powerful electric shock and noted with satisfaction that all the monks started swearing and contorting, reacting simultaneously to the shock. A second demonstration was performed at Versailles for King Louis XV, this time by sending current through a chain of 180 Royal Guards since by now the monks were less than cooperative. The King was both impressed and amused as the soldiers all jumped simultaneously when the circuit was completed.

1747 - 1753 Wealthy, eccentric English loner Henry **Cavendish** discovered the concept of **electric potential**, that the **Inverse Square Law** applied to the force between electric charges, that the **capacity of a condenser** depends on the substance between the plates (the **dielectric**) and that the potential across a conductor is proportional to the current through it (**Ohm's Law**).
Charge was provided by **Leyden Jars**. Potential was "measured" by observing the deflection of the two gold leaves of an electrometer but since no instruments for the measurement of electric current existed at the time, Cavendish simply shocked himself, and estimated the current on the basis of the extent and magnitude of the resulting pain.
Cavendish recorded all his experiments in notebooks and manuscripts but published very little, principally the results of the chemical experiments which formed the bulk of his work. It was therefore left to **Coulomb** (1785), **Ohm** (1827) and **Faraday** (1837) to rediscover these laws many years afterwards. His papers were discovered over a century later by James Clerk **Maxwell** who annotated and published them in 1879.
Cavendish's family endowed the Cambridge University Cavendish Laboratories at which many of the world's discoveries in the field of nuclear physics were made.

1747 British physicist Sir William **Watson**, Bishop of Landaff, ran a wire on insulators across Westminster Bridge over the Thames to a point across the river over 12,000 feet away. Using an **earth** or **ground return** through the river. He was able to send a charge sufficiently intense after passing through three people to ignite spirits of wine. Watson was probably the first man to use ground conduction of electricity, though he may not have been aware of its significance at the time. Watson was the first to recognise that a discharge of static electricity is equivalent to an electric current.

1748 Watson uses an electrostatic machine and a vacuum pump to make a **glow discharge** lamp. His glass vessel was three feet long and three inches in diameter. The first **fluorescent light bulb**.

1748 To carry out measurements with less risk of electrocution of the experimenter or dragooned assistants **Nollet** invented one of the first **electrometers**, the **electroscope**, which detected the presence of **electric charge** by using electrostatic attraction and repulsion between two pieces of metallic foil, usually gold leaf, mounted on a conducting rod which is insulated from its surroundings. The first **voltmeters**.

1750 Nollet demonstrated the astonishing efficiency of **electrostatic spraying**, an idea which was not put to practical use until it was rediscovered by Ransburg in 1941.

1750 English physicist John **Michell** describes **magnetic induction**, the production of magnetic properties in unmagnetised iron or other ferromagnetic material when it is brought close to a magnet. He discovered that the two poles of a magnet are of equal strength and that they obey the **inverse-square law for magnetic attraction** in "A Treatise on Artificial Magnets".

1752 French experimenter Thomas François **Dalibard**, assisted by retired illiterate old dragoon M. **Coiffier**, carried out an experiment proposed by Benjamin Franklin. From a safe distance (in Dalibard's case eighteen miles away) they used a long pointed iron rod, insulated from the ground by glass bottles, to attract a lightning discharge from a thunder cloud. Coiffier subsequently drew electrical sparks from the charged rod to prove that thunder clouds contain **electricity** and that it can be **conducted** down a metal rod.

1752 Johann Georg **Sulzer** notices a tingling sensation when he puts two dissimilar metals, just touching eachother, on either side of his tongue. It became known later as the **battery tongue test**: - the saliva acting as the electrolyte carrying the current between the two metallic electrodes.

1752 A man of many talents, Benjamin **Franklin** one of the leaders of the American Revolution and founding fathers of the USA, journalist, publisher, author, philanthropist, abolitionist, public servant, scientist, diplomat and inventor carried out his kite experiments in 1752, one month after **Dalibard**, and invented the **lightning rod**. He proposed a "fluid" theory of electricity and outlined the concepts of **positive and negative charges, current flow and conductors** coining the language to describe them. Words such as **battery** (from an array of charged glass plates, and later, a number of Leyden Jars), charge, condenser (capacitor), conductor, plus, minus, positively, negatively, armature, electric shock and electrician which we still use today.

Whilst it may be heresy to suggest that Franklin did not carry out the kite experiment for which he is famous, there are no reliable witnesses to this event and it is a fact that nobody, including Franklin, has yet been able to duplicate this experiment in the manner he described, and few have been willing to try. One who did was Professor Georg W **Richmann** a Swedish physicist working in St Petersburg who was killed in the attempt on 6 August 1753. He was the first known victim of high voltage experiments in the history of physics. Benjamin Franklin was lucky not to win this honour.

1753 A proposal is submitted in an anonymous letter to the Scotsman Magazine signed "C.M.", generally attributed to Scottish surgeon Charles **Morrison**, for 'An Expeditious Method of Conveying Intelligence'. It described an **electrostatic telegraph system** using 26 insulated wires to conduct separate charges from a Leyden Jar causing movements in small pieces of paper on which each letter of the alphabet is written.

1757 French botanist Michel **Adanson** proposed that the discharge from the Senegalese (electric) catfish could be compared with the discharge from a **Leyden jar**. The ability of certain torpedo fish or sting rays to inflict electric shocks had been known since antiquity however Adanson's theory was new. It was later proved by British administrator and M.P., John **Walsh**, secretary to Clive of India, who in 1772 managed to draw a spark from an **electric eel**. It is quite possible that news of Walsh's experiment influenced Galvani to begin his own experiments with frogs.

1759 German mathematician Franz Maria Ulrich Theodosius **Aepinus** published his book, **An Attempt at a Theory of Electricity and**

Magnetism. The first work to apply mathematics to the theory of electricity and magnetism, it explained most of the then known phenomena.
In 1889 Aepinus also made the first **variable capacitor** which he used to investigate the properties of dielectrics. It had flat plates which could be moved apart and different materials could be inserted between them. **Volta** also laid claim to the invention of this device and to giving it the name of "capacitor".

1761 Scottish chemist and physicist Joseph **Black** working at Glasgow University, discovered that ice absorbs heat without changing temperature when melting. Between 1759 and 1763 he evolved the theory of **latent heat** for a heat flow that results in no change of temperature, that is, for the heat flows which accompany phase transitions such as boiling or freezing. He also showed that different substances have different specific heats, the amount of heat per unit mass required to raise its temperature by one degree Celsius.
James Watt was his pupil and assistant.

1766 Swiss physicist, geologist and early Alpine explorer Horace Benedict **de Saussure** invents the first true **electrometer** for measuring electric potential by means of attraction or repulsion of charged bodies. It consisted of two pith balls suspended by separate strings inside an inverted glass jar with a printed scale so that the distance or angle between the balls could be measured. It was de Saussure who discovered the distance between the balls was not linearly related to the amount of charge.

1767 English clergyman, philosopher and social reformer Joseph **Priestley** at the age of 34 made his first foray into the world of science with the publication of a two-volume **History of Electricity** in which he argued that the history of science was important since it could show how human intelligence discovers and directs the forces of nature. The previous year in London he had met Benjamin **Franklin** who introduced him to the wonders of electricity and they became lifelong friends. Priestley's first discovery, also in 1767, was that carbon conducts electricity.

Though he had no scientific training, Priestley is however better known as a chemist. He isolated Carbon dioxide, which he called "fixed air", and in a paper published in 1772, he showed that a pleasant drink could be made by dissolving the gas in water. Thus was born carbonated (soda) water, the basis of the modern soft drinks industry.
He was a great experimenter discovering Nitrous oxide (laughing gas) and several other chemical compounds and unaware of the work of **Scheele** he independently discovered Oxygen. Priestley was no theorist however and he passed on his results to the French chemist **Lavoisier** who repeated the experiments taking meticulous measurements in search of underlying patterns and laws governing the chemical reactions. Experimenting with growing plants in an atmosphere of Carbon dioxide, Priestley observed that the plants consumed the Carbon dioxide and produced Oxygen, identifying the process of **plant respiration** and **photosynthesis**. This was the first connection between **chemistry and biology**.

As a reformer, Priestley was a strong supporter of the 1776 American and the 1789 French Revolutions. This brought him into conflict with conservatives and in 1791 angry mobs burnt down his house and his church destroying many of his manuscripts. The intimidation continued until 1794 when the aristocratic Lavoisier, on the opposite side of the revolutionary fence from Priestley, was executed by French revolutionaries. A few weeks later Priestley emigrated to America to escape persecution spending the rest of his life there.

1769 The large scale generation of electricity could never have happened without James **Watt**'s **steam engine** which for many years, apart from a few hydroelectric schemes, was the **prime mover** for driving electric generators. Starting in 1769 Watt made a series of improvements to the steam engine originally patented in 1698 by the English engineer Thomas **Savery** in and improved by Thomas **Newcomen** in 1712. Watt's major contribution was the addition of a separate condenser, for condensing the steam, that could be kept cool while the working cylinder remained hot, thus reducing heat losses on every cycle and improving the efficiency of the machine. The introduction of Watt's steam engine was a key event in the **Industrial Revolution**.

1771 The world's first **machine powered factory** began operations in Cromford, Derbyshire. English inventor Richard **Arkwright** pioneered large scale manufacturing using a water wheel to replace manual labour used to power the spinning frames in his cotton mill.

1774 An **electrostatic telegraph** is demonstrated in Geneva, Switzerland by Frenchman George Louis **LeSage**. He built a device composed of 24 wires each contained in a glass tube to insulate the wires from eachother. At the end of each wire was a pith ball which was repelled when a current was initiated on that particular wire. Each wire stood for a different letter of the alphabet. When a particular pith ball moved, it represented the transmission of the corresponding letter. Intelligible messages were transmitted over short distances and LeSage's system is considered to be the first serious attempt at making an electrical telegraph.

1775 Like many experimenters of his time Alessandro **Volta** constructed his own **Perpetual Electrophorus** (that which carries off electricity) to provide a regular source of electricity for his experiments. It was crude and consisted of a resin plate on which was rubbed cat's fur or a fox tail and another insulated metal plate for picking up the charge.

1775 In response to the demands of the armaments industry the nascent steam power industry English engineer John **Wilkinson** made one of the first **precision machine tools**, a cylinder boring machine. His machine secured for him the largest share in the profitable business of supplying cannons in the American War of Independence. Wilkinson is reputed to be Britain's first industrialist to become a millionaire.

1782 French mathematician Pierre-Simon **Laplace**, building on earlier work by Swiss mathematician Leonhard **Euler**, develops a mathematical operation now called the **Laplace Transform** as a tool for solving linear **differential equations**. The most significant advantage is that differentiation and integration become multiplication and division, respectively. This is similar to the way that logarithms change an operation of multiplication of numbers into the simpler addition of their logarithms. By applying Laplace's **integral transform** to each individual term in differential equations, the terms can be rewritten in terms of a new variable "s" and the equations are converted into polynomial equations which are much easier to solve by simple algebra. The solutions to the original problems are retrieved by applying the **Inverse Laplace Transform**. This technique simplifies the analysis control systems and analogue circuits which are characterised by time varying differential equations. Laplace's method thus transforms differential equations in the **time domain** into algebraic equations in the **s-domain**.

Between 1799 and 1825 Laplace published in five volumes "Traité de Mécanique Céleste", **Celestial Mechanics**, in which he translated the geometrical study of mechanics used by **Newton** to one based on calculus.

Laplace also developed the foundations of **probability theory** which he published in 1812 as "Théorie Analytique des Probabilités". Prior to that, probability theory was solely concerned with developing a mathematical analysis of games of chance. Laplace applied the theory to the analysis of many practical problems in the social, medical, and juridical fields as well as in the physical sciences including mortality, actuarial mathematics, insurance risks, the theory of errors, statistical mechanics and the drawing of statistical inferences.

In 1799 Laplace was appointed by **Napoleon** as Minister of the Interior but he was removed after only six weeks "because he brought the spirit of the infinitely small into the government".

1784 Cavendish demonstrated that water is produced when hydrogen burns in air, thus proving that **water is a compound** of two gases and not an element and overturning over two thousand years of conventional wisdom.

1784 King **Louis XVI** of France set up a Royal Commission to evaluate the claims by German healer and specialist in diseases of the wealthy, Franz Anton **Mesmer** who had achieved international notoriety with his theory **animal magnetism** and its supposed therapeutic powers. Members of the committee included Benjamin **Franklin**, Antoine **Lavoisier** and the physician Joseph-Ignace **Guillotin**, inventor of the Guillotine which was later used to remove the heads of both Lavoisier and the King. Mesmer had claimed extraordinary powers to cure patients of various ailments by using magnets. He also claimed to be able to magnetise virtually anything including paper, wood, leather, water, even the patients themselves and that he himself was a source of animal magnetism, a magnetic personality. His clients were mainly aristocratic women many of whom reported pleasurable experiences as Mesmer moved his hands around their bodies to align the flow of magnetic fluid while they were in a trance. Mesmer was a patron of the composer Wolfgang Amadeus **Mozart** who included a scene in which Mesmer's magnets were used to revive victims of poisoning in the opera "Cosi fan tutte". The committee however concluded that all Mesmer's observed effects could be attributed to the power of suggestion and he was denounced as a fraud. He did however keep his head (the French revolution was still four years away) and his name lives on as hypnotists **mesmerise** their subjects.
Guillotin by the way was not a revolutionary. As a physician he merely proposed the guillotine as a more humane method of execution rather than hacking away with a sword.

1785 French military engineer and physicist, Charles-Augustin de **Coulomb** published the correct quantitative description of the force between electrical charges, the **Inverse Square Law**, which he verified using a sensitive torsion balance which he had invented in 1777. He showed that the electrical charge is on the surface of the charged body. Coulomb's Law was the first quantitative law in the history of electricity.
Coulomb also founded the science of friction.
The unit of charge is named the Coulomb in his honour.

1786 Luigi **Galvani** professor of anatomy at Bologna Academy of Science in Italy discovered that two dissimilar metals applied to the leg of a dead frog would make it twitch although he believed that the source of the electricity was in the frog. He was quite possibly influenced in his conclusions by the knowledge of **Walsh**'s experiments with **electric fish**. Could it be **animal electricity?**. He found copper and zinc to be very effective in making the muscles twitch. His friend **Volta** on the other hand believed the electricity came from the metals and for many years a debate raged until it was eventually resolved by Volta's invention of the Voltaic pile. In the meantime Galvani lost his job for refusing to swear allegiance to **Napoleon**'s Cisalpine Republic whereas Volta attempted to accommodate Napoleon and prospered under his rule. Sadly Galvani died in 1798 without knowing the outcome of the debate.

1787 Experiments by French physicist and chemist Jacques **Charles** (later continued by Joseph Louis **Gay-Lussac**) revealed that:

- All gases expand or contract at the same rate with changes in temperature provided the pressure is unchanged.
- The change in volume amounts to 1/273 of the original volume at 0°C for each Celsius degree the temperature is changed.

This work provided the inspiration for **Kelvin**'s subsequent theories on **thermodynamics**.

Charles' Law and Gay Lussac's Law together with **Boyle's Law** are known collectively as the **Gas Laws**.

In his spare time, Charles was an enthusiastic balloonist making several ascents and improving ballooning equipment.

1789 French chemist Antoine Laurent **Lavoisier** considered to be the founder of modern chemical science, published **Traité Élémentaire de Chimie** or "Elementary Treatise of Chemistry", the first modern chemistry textbook. In it he presented a unified view of new theories of chemistry and a clear statement of the **Law of Conservation of Mass** which he had established in 1772. In addition, he defined **elements** as substances which could not be broken down further and listed all known elements at the time including oxygen, nitrogen, hydrogen, phosphorus, mercury, zinc, and sulphur. As intended, it did for chemistry what **Newton's Principia** had done for physics one hundred years earlier.

Lavoisier was the first to apply rigorous scientific method to chemistry. He carried out his experiments on chemical reactions with meticulous precision devising closed systems to ensure that all the products of the reactions were measured and accounted for. He thus demolished the wild ideas of the alchemists as well as the **Greek concept** of four elements, earth, air, fire and water which had been accepted for over 2000 years.

Lavoisier had a wide range of interests and a prodigious appetite for work and funded his experiments from his part time job as a tax collector. He was aided in his scientific endeavours by his wife Marie-Anne Pierrette Paulze, whom he had married when she was only thirteen years old. The couple were at the centre of a Parisian social life, but in 1794 Lavoisier's tax collecting activities fell foul of France's revolutionary mob and he was **Guillotined** during the Reign of Terror. An appeal to spare his life was cut short by the judge with the words "The Republic has no need of scientists".
Afterwards the French mathematician Joseph-Louis **Lagrange** said "It took them only an instant to cut off that head, and a hundred years may not produce another like it".

See also Lavoisier's relationship with **Rumford**

1790 The first **patent laws** established un the USA by a group led by Thomas **Jefferson**. Until US Independence, when **Intellectual Property Rights** were protected by the American Constitution, the King of England officially owned the intellectual property created by the colonists. Patents had however been issued by the colonial governments and were protected by British law.
The first US patent was granted to Samuel **Hopkins** of Vermont for a new method of making Potash.

1791 German chemist and mathematician Jeremias Benjamin **Richter** attempted to prove that chemistry could be explained by mathematical relationships. He showed that such a relationship applied when acids and bases neutralize to produce salts they do so in **fixed proportions.** Thus he was the first to establish the basis of **quantitative chemical analysis** which he named **stoichiometry**. He died of tuberculosis at the age of 45.

1795 The **hydraulic press** used for metal forming invented by English engineer Joseph **Bramah**.

1797 Young Prussian noble Alexander **von Humboldt** published a book outlining his theories about **Galvanic electricity** and his experiments to support them. He believed that the electricity came from the muscle and was intensified by the electrodes and he carried out experiments on plants and animals to prove it. He also carried out numerous experiments on himself to gather more data using a Leyden jar to inflict severe shocks on his body until it was badly lacerated and scarred. He was mortified three years later when his theories were proved completely wrong by **Volta** and turned his attention instead to geology, botany and exploration in all of which he found international fame but no fortune.

1797 English engineer Henry **Maudslay** introduced the **precision screw-cutting lathe**. Although lathes had been in use from before 3000 B.C. when the **Egyptians** used the **bow lathe** for wood turning, Maudslay's lathe was the first true ancestor of the modern **machine tools** industry. He raised the standards of precision, fits, finishes and metrology and invented the first bench micrometer capable of measuring to one ten thousandth of an inch which he called the "Lord Chancellor" because it resolved disputes about the accuracy of workmanship in his factory.
Maudslay's pupils included Scottish engineer James **Naysmith** who designed and made heavy machine tools, including the **shaper** and the **steam hammer**, for the ship building and railway industries and English engineer Joseph **Whitworth** who worked on **Babbage**'s Difference Engine and later introduced the **Whitworth standard system** for screw-cutting threads which was first adopted by the railways and the Woolwich Arsenal and then became an **industry standard** enabling **interchangeability of components** and **production automation**. See also **Whitney** - next.

1798 In an age when mechanical devices were individually made and laboriously fitted by hand, American engineer Eli **Whitney** pioneered the concept of **interchangeable parts** in the USA, using precision manufacturing made possible by more accurate machine tools just becoming available. Prior to that, if a part failed, a replacement part had to be made and fitted individually creating major problems and losses in battlefield conditions. Whitney's methods also reduced the skill levels needed to manufacture and assemble the parts enabling him to take on a contract to supply 10,000 muskets in two years to the US government. Whitney also built a rudimentary **milling machine** in 1818 for use in firearms manufacturing, but the **universal milling machine** as we would recognise it today was invented by American engineer Joseph Rogers **Brown** in 1862. Brown's machine was able to cut the flutes in twist drills. Since the introduction of twist drills in the 1820's these flutes had been filed by hand.

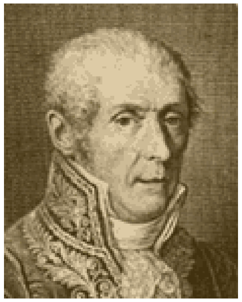
1799 Count **Rumford,** man of science, inventor, administrator, philanthropist, self publicist and scoundrel, born Benjamin Thompson in the USA, founded **The Royal Institution** in London to promote and disseminate the new found knowledge of the industrial revolution. Its first director was a well connected, glamorous young Cornish chemist, Humphry **Davy**. Davy was a great showman, but did not consider "common mechanics" worthy of his brilliance, so the Institution rapidly evolved to presenting lectures for the wealthy, who paid to attend. In Rumford's original plan, there had been a back door through which the poor could access a balcony to hear the lectures from a distance for free. Davy had it bricked up. The Institution did, however, perform a very valuable function in that it was a subsidised science lab, one of the very few in the world, which enabled scientists of the day, such as Michael Faraday, to make many important discoveries.

Rumford was a colourful character, like fellow American Benjamin Franklin, a man of many talents. Raised in pre-Revolutionary New England, at the age of 19 he married a wealthy 31-year-old widow and he took up spying on the colonies for the British but left for England in 1776 when he was found out, deserting his wife and daughter. At first he worked in the British foreign office as undersecretary for Colonial Affairs and was knighted by George III after a stint in the army fighting on the British side in the American War of Independence. He moved on to Munich where he carried out public and military works for the Elector of Bavaria being rewarded in 1792 with the title Count of the Holy Roman Empire. Among his inventions were the drip coffee pot and thermal underwear.

His interest in field artillery led him to study both the boring and firing of cannons. Out of this work he saw that mechanical power could be converted to heat -- that there was a direct **equivalence between thermal energy and mechanical work**. Heat was produced by friction in unlimited quantities so long as the work continued. It could therefore not be a fluid called a **Caloric** flowing in and out of a substance as his adversary, the noted French chemist, Antoine Lavoisier, had proposed, since the fluid would have a finite quantity.

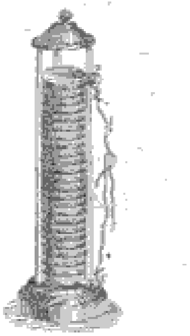
After Lavoisier's death Rumford started a four year affair with his wealthy, young widow, however after a short unhappy marriage they divorced with Rumford remarking that Lavoisier was lucky to have been guillotined. Rumford lived out the rest of his life in Lavoisier's former house in France engaged in scientific studies and it is claimed that he was paid by the French for spying on the British.

1800



Alessandro Volta

Thee man who started it all.



Volta's Pile

Alessandro **Volta** of the University of Pavia, Italy, describes the principle of the electrochemical battery in a letter to the Royal Society in London. The first device to produce continuous electric current. He had been interested in electrical phenomena since 1763 and in 1775 he had made his own electrophorus for carrying out his experiments. He was a friend of Galvani but disagreed with him about the nature of electricity. Galvani's experiments with frogs had led him to believe that the source of the electricity was the frog, however Volta sought to prove that the electricity came from the dissimilar metals used to probe the specimen.

His "**Voltaic Pile**" was initially presented in 1800 as an "artificial electric organ" to demonstrate that the electricity was independent of the frog. It was constructed from pairs of dissimilar metals zinc and silver separated by a fibrous diaphragm (Cardboard?) moistened with sodium hydroxide or brine and provided the world's first continuous electric current. The pile produced a voltage of between one and two volts. To produce a higher voltages he connected several piles together with metal strips to form a "battery". He was the first to understand the importance of "closing the circuit".

Volta's invention caused great excitement at the time and he gave many demonstrations including drawing sparks from the pile, melting a steel wire (the first fuse?), discharging an electric pistol and decomposing water into its elements. **Napoleon** was particularly impressed, insisting on helping with the demonstrations when he was present and showering Volta with honours despite the fact that France and Italy were initially at war with each other. The unit of electric potential was named the Volt in his honour.

After the invention of the battery, Volta was awarded a pension by Napoleon and he began to devote more of his time to politics, holding various public offices. He retired in 1819 and died in 1827 and although the battery was a sensation in scientific circles and giving impetus to an intensification of scientific investigation and discovery throughout the nineteenth century, surprisingly Volta himself never participated in these opportunities.

1800 English scientists, William **Nicholson** and Anthony **Carlisle**, experimenting with Volta's chemical battery, accidentally discovered **electrolysis**, the process in which an electric current produces a chemical reaction, and initiated the science of **electrochemistry**. (A discovery like many others claimed by Humphry **Davy** though he did actually do original work at a later date on electrolysis).

This new technique, made possible by the availability of the constant electric current provided by the new found batteries, enabled many compounds to be separated into their constituent elements and led to the discovery and isolation of many previously unknown chemical elements. Electrolysis, "loosening with electricity", thus became widely used by scientific experimenters.

1801 French silk-weaver, Joseph-Marie **Jacquard** invented an **automatic loom** using **punched cards** to control the weaving of the patterns in the fabrics. This was not the earliest implementation of a **stored program** and the use of punched cards programmed to control a manufacturing process as is often claimed. That honour goes to **Bouchon** starting in 75 years earlier and improved by **Falcon** in 1728 and eventually refined by **de Vaucanson** in 1744. Jacquard presented his invention in Paris in 1804, and was awarded a medal and patent for his design by the French government who consequently claimed the loom to be public property, paying Jacquard a small royalty and a pension. Its introduction caused riots in the streets by workers fearing for their jobs.

Despite the loom's fame, Jacquard's principles of **programmed control** and **automation** were not applied to any other manufacturing process for another 145 years when **Parsons** produced the first numerically controlled machine tools.

1801 Frenchman Nicholas **Gautherot** observed that when a current from a voltaic battery was sent between two Copper plates immersed in Sulphuric acid, for a short period afterwards the copper plates could drive a current back in the opposite direction. He had inadvertently discovered the **rechargeable battery** but did not realise its significance. Sixty years later **Planté** repeated the experiment with Lead plates and the Lead Acid battery was born.

1802 English chemist Dr William **Cruikshank** designed the first battery capable of mass production. A flooded cell battery constructed from sheets of copper and zinc in a wooden box filled with brine or acid.

Cruikshank also discovered the **electrodeposition** of copper on the cathodes of copper based electrolytic cells and was able to extract metals from their solutions, the basis modern **metal refining** and of **electroplating**, but it was not until 1840 that the commercial potential of the plating process was realised by the **Elkingtons**.

1803 Johann Wilhelm **Ritter**, a German physicist, first demonstrated the elements of a **rechargeable battery** made from layered discs of copper and cardboard soaked in brine. Unfortunately there was no practical way to recharge it other than from a Voltaic Pile and for many years they remained a laboratory curiosity until someone invented a charger. Ritter was one of the first to identify the phenomenon of **polarisation** in acidic cells. He also repeated Galvani's "frog" experiments with progressively higher voltages on his own body. This was probably the cause of his untimely death at the age of 33.
In 1801 after studying the discovery of infrared radiation the previous year by German born English astronomer, Frederick William **Herschel**, Ritter discovered the ultraviolet region of the spectrum.

1803 John **Dalton** a Quaker school teacher working in Manchester resurrects the Greek **Democritus**' **atomic theory** that every element is made up from tiny identical particles called **atoms**, each with a characteristic mass, which can neither be created or destroyed. Dalton showed that elements combine in **definite proportions** and developed the first list of **atomic weights** which he first published in 1803 at the Manchester Literary and Philosophical Society and at greater length in book form in **1808**.

1804 The **Electric telegraph** one of the first attempted applications of the new electric battery technology was proposed by Catalan scientist Francisco **Salvá**. One wire was used for each letter of the alphabet and each number. The presence of a signal was indicated by a stream of hydrogen bubbles when the telegraph wire was immersed in acid. The system had a range of one kilometer.

1805 Italian chemist Luigi Valentino **Brugnatelli**, friend of **Volta** demonstrated **electroplating** by coating a silver medal with gold. He made the medal the cathode in a solution of a salt of gold, and used a plate of gold for the anode. Current was supplied by a Voltaic pile. Brugnatelli's work was however rebuffed by **Napoleon Bonaparte** which discouraged him from continuing his work on electroplating.
The process later became widely used for rust proofing and for providing decorative coatings on cheaper metals. Gold plating is used extensively today in the electronics industry to provide low resistance, hard wearing, corrosion proof connectors.

1807 English physician, physicist, and Egyptologist Robert **Young** introduced a measure of the stiffness or **elasticity** of a material, now called **Young's Modulus** which relates the deformation of a solid to the force applied. Also called the **Modulus of elasticity** it can be thought of as the **spring constant** for solids. Young's modulus is a fundamental property of the material. It enables **Hooke's spring constant**, and thus the energy stored in the spring to be calculated from a knowledge of the elasticity of the spring material.
Young was the first to assign the term **kinetic energy** to the quantity **$\frac{1}{2}MV^2$** and to define **work done**, as **force X distance** which is also equivalent to energy, an extension to **Newton's Laws** but surprisingly taking 140 years to emerge. More surprising still is that it was another 44 years before the concept of **potential energy** was proposed.

He also did valuable work on optical theory and in 1801 he devised the **Double slit interference** experiment which verified the **wave nature of light**.

Young is considered by some to be the last person to know everything there was to know. (Not the only candidate to this fame). He was a child prodigy and had read through the Bible twice by the age of four and was reading and writing Latin at six. By the time he was 14 he had a knowledge of at least five languages, and eventually his repertoire grew to 12. He practised medicine until the work load clashed with his other interests, and among his many accomplishments he translated the inscriptions on the Rosetta Stone which was they key which enabled hieroglyphics to be deciphered.

1807 Humphry **Davy** constructed the largest battery ever built at the time, with over 250 cells, and passed a strong electric current through solutions of various compounds suspected of containing undiscovered elements isolating potassium and sodium by this electrolytic method, followed in 1808 with the isolation of calcium, strontium, barium, and magnesium. The following year Davy used his batteries to create an **arc lamp**.

In 1813 Davy wrote to the Royal Society stating that he had identified a new element which he called iodine, four days after a similar announcement by **Gay-Lussac**. The element had in fact been isolated in 1811 from the ashes of burnt seaweed by Bernard **Courtois**, the son of a French saltpetre manufacturer, who had passed samples to Gay-Lussac and **Ampère** for investigation. Ampère in turn passed a sample to Davy. Although Courtois discovery was not disputed, both Davy and Gay-Lussac both claimed credit for identifying the element.

1807 As a result of his studies on heat propagation, French mathematician Baron Jean Baptiste Joseph **Fourier** presented a paper to the Institut de France on the use of simple sinusoids to represent temperature distributions. The paper also claimed that any continuous periodic signal could be represented as the sum of properly chosen sinusoidal waves.

For the previous fifty years the great mathematicians of the day had sought equations to describe the vibration of a taut string anchored at both ends as well as the related problem of the propagation of sound through an elastic medium. French mathematicians Jean **d'Alembert** and Joseph-Louis **Lagrange** and Swiss Leonhard **Euler** and Daniel **Bernoulli** had already proposed combinations of sinusoids to represent these physical phenomena and in Germany, Carl Friedrich **Gauss** had also been working on similar ways to analyse mechanical oscillations (see below). Whereas their theories applied to particular situations, Fourier's claim was controversial in that it extended the theory to *any* continuous periodic waveform.

Among the reviewers of Fourier's paper were Lagrange, Adrien-Marie **Legendre** and Pierre Simon de **Laplace**, some of history's most famous mathematicians. While Laplace and the other reviewers voted to publish the paper, Lagrange demurred, insisting that signals with abrupt transitions or "corners", such as square waves could not be represented by smooth sinusoids. The Institut de France bowed to the prestige of Lagrange, and rejected Fourier's work. It was only after Lagrange died that the paper was finally published, some 15 years later.

When Fourier's paper was eventually published in 1822, it was restated and expanded as "Theorie Analytique de la Chaleur", the mathematical theory of **heat conduction**. The study made important breakthroughs in two areas. In the study of heat flow, Fourier showed that the rate of **heat transfer** is proportional to the **temperature gradient**, a new concept at the time, now known as **Fourier's Law**.

Of greater importance however were the mathematical techniques Fourier developed to calculate the heat flow in unusually shaped objects. He provided the mathematical proof to support his 1807 claim that any repetitive waveform can be approximated by a series of sine and cosine functions, the coefficients of which we now call the **Fourier Series**. These coefficients represent the magnitudes of the different frequency components which make up the original signal. When the sine and cosine waves of the appropriate frequencies are multiplied by their corresponding coefficients and then added together, the original signal waveform is exactly reconstructed. Thus complex functions such as differential equations can be converted into simpler trigonometric terms which are easier to handle mathematically by calculus or other methods.

This mathematical technique is known as the **Fourier transform** and its application to an electrical signal or mechanical wave is analogous to the splitting or "dispersion" of a light beam by a prism into the familiar coloured optical spectrum of the light source. An optical spectrum consists of bands of colour corresponding to the various wavelengths (and hence different frequencies) of light waves emitted by the source. In the same way, applying the Fourier transform to an electrical signal separates it into its spectrum of different frequency components, often called harmonics, which makes it very useful in electrical engineering applications.

In electrical engineering applications, the Fourier transform takes a **time series** representation of a complex waveform and converts it into a **frequency spectrum**. That is, it transforms a function in the **time domain** into a series in the **frequency domain**, thus decomposing a waveform into **harmonics** of different frequencies, a process which was formerly called **harmonic analysis**.

The Fourier Transform has wide ranging applications in many branches of science and while many contributed to the field, Fourier is honoured for his insight into the practical usefulness of the mathematical techniques involved.

Fourier led an exciting life. He was a supporter of the Revolution in France but opposed the Reign of Terror which followed bringing him into conflict and danger from both sides. In 1798 he accompanied **Napoleon** on his invasion of Egypt as scientific advisor but was abandoned there when **Nelson** destroyed the French fleet in the battle of the Nile. Back in France he later provoked Napoleon's ire by pledging his loyalty to the king after Napoleon's abdication and the fall of Paris to the European coalition forces in 1814. When Napoleon escaped from Elba in 1815 Fourier once more feared for his life. His fears were unfounded however and, despite his disloyalty, Napoleon awarded him a pension but it was never paid since Napoleon was defeated at Waterloo later that year.

As noted above Fourier was not the only one at the time looking for simple solutions to complex mathematical problems. Gauss was trying to calculate the trajectories of the asteroids Pallas and Juno. He knew that they were complex repetitive functions but he only had sampled data of the locations at particular points in time rather than a continuous time varying function from which to construct a mathematical model of the trajectories. Although this was before Fourier's time, like his contemporaries Gauss was aware that the result should be a series of sinusoids, but deriving a transform from sampled or discrete data, rather than from a time varying mathematical function, involves a huge computational task. Such a transform applied to **sampled data** is now known as a **Discrete Fourier Transform (DFT)** and can be considered as a digital tool whereas the general Fourier Transform only applies to **continuous functions** and can be considered as an analogue tool. In 1805 Gauss derived a mathematical short cut for computing the coefficients of his transform. Although he applied it to a specific, rather than a general case, we would recognise Gauss's short cut today as the **Fast Fourier Transform (FFT)** even though it owed nothing to Fourier.

1808 Prolific Swedish chemist Jöns Jacob **Berzelius** working at the University of Uppsala in Sweden formulated the **Law of Definite Proportions** (discovered by **Dalton** five years earlier and by **Richter** twelve years before that) which establishes that the elements of inorganic compounds are bound together in definite proportions by weight. Berzelius developed the system of **chemical notation** we still use today in which the elements were given simple written labels, such as O for oxygen, or Fe for iron, and proportions were noted with numbers. He accurately determined the relative atomic and molecular masses of over 2000 elements and compounds.

1808 Mark Isambard **Brunel**, father of famous son Isambard Kingdom Brunel, with the task of manufacturing 60,000 wooden pulley blocks per year, set up one of the first ever **mass production lines**. Instead of one man making a complete pulley Brunel divided the work into a series of simple, short cycle, repetitive tasks and using 43 purpose-built precision machines from **Maudslay** to carry out the sequential operations in line, he reduced the labour required to do the work from 110 to 10. A formula which has become an industry standard.

1809 Davy produced an electric arc between two carbon electrodes - the first **electric light**. Davy is generally credited with inventing the **carbon arc lamp**, however a Russian Vasilli V. **Petrov** had reported this phenomenon in 1803.
In 1816 Davy claimed the credit for the invention of the miner's safety lamp, named the "Davy lamp" in his honour but it was actually similar to a design already demonstrated in 1815 by self taught railway pioneer **George Stephenson**. The privileged Davy was incensed that he could be upstaged by working class Stephenson.

According to J. D. Bernal's "Science in History" Davy is quoted as saying "The unequal division of property and of labour, the difference of rank and position amongst mankind, are the sources of power in civilized life, its moving causes, and even its very soul."

See also Davy and the **Royal Institution**

1810

1811 Italian physicist Amadeo **Avogadro** discovered the concept of **molecules**. He hypothesized that equal volumes of gases at the same temperature and pressure contain equal numbers of molecules. From this **hypothesis** it followed that relative molecular weights of any two gases are the same as the ratio of the densities of the two gases under the same conditions of temperature and pressure.
The basic scheme of atoms and molecules arrived at by **Dalton** and Avogadro underpins all modern chemistry.

1812 German physician Samuel Thomas **von Sömmering** increased the range of **Salvá**s (1804) **telegraph** to three kilometers by using bigger batteries, a method subsequently used with disastrous results on the **Transatlantic Telegraph Cable**.

1812 Venetian priest and physicist Giuseppe **Zamboni** developed the first leak proof **high voltage "dry" batteries** with terminal voltages of over 2000 Volts. They consisted of thousands of small metallic foil discs of tin or an alloy of copper and zinc called "tombacco", separated by paper discs stacked in glass tubes. The technology was not well understood at the time and while Zamboni consciously avoided the use of any conventional corrosive aqueous electrolyte in the cells, hence the name "dry" battery, the electrolyte was actually provided by the humidity in the paper discs and a variety of experimental greasy acidic pulps spread thinly on the foils to minimise polarisation effects. Although the battery voltage was very high, the internal resistance was thousands of megohms so the current drawn from the batteries was about 10^{-9} amps, limiting the battery's potential applications. One notable application however was a primitive **electrostatic clock** mechanism in which a pendulum was attracted towards the high voltage terminal of a **Zamboni pile** by the electrostatic force between the pendulum and the terminal. When the pendulum touched the terminal it acquired the same charge as the terminal and was consequently deflected away from it towards the opposite pole of another similar pile from which, by a similar mechanism it was deflected back again, thus maintaining the oscillation. The current drain or discharge rate of the batteries was so low as to be undetectable with instruments available at the time and it was thought that the pendulum was a **"perpetual electromotor"**. In fact Zamboni primary batteries have been known to last for over 50 years before becoming completely discharged!

1813 French mathematician and physicist Siméon Denis **Poisson** derived the relationship which relates the **electric potential** in a static electric field to the **charge density** which gives rise to it. The resulting **electric field** is equal to the gradient of the potential. This equation describes the **electric fields** which drive the flow of charged ions through the electrolyte in a battery.
Poisson published many papers during his lifetime but he is perhaps best remembered for his 1837 paper on the statistical distribution now named after him. The **Poisson distribution** describes the probability that a random event will occur in a time or space interval under the conditions that the probability of the event occurring is very small, but the number of trials is very large so that the event actually occurs only a small number of times. He used his theory to predict the likelihood of being killed by being kicked by a horse and tested it against French army records over several years of the number of soldiers killed in this way. Apart from analysing accident data, the distribution is fundamental to **queueing theory** which is used in **traffic studies** to dimension applications from supermarket checkouts and tollgates to telephone exchanges.

1816 A two wire **telegraph** system based on high voltage static electricity activating pith balls, using synchronous clockwork dials at each end of the channel to identify the letters, was demonstrated in the UK by Francis **Ronalds,** an English cheese maker and experimental chemist, and subsequently described in his publication of 1823. Coming only a year after Wellington's victory over Napoleon at Waterloo, it was turned down by the haughty Admiralty, who had just invented semaphore signalling, with the comment "Telegraphs of any kind are now wholly unnecessary". It was an invention before its time and nobody showed any interest. At the time it was however witnessed by the young Charles **Wheatstone** who was later credited in the UK with the invention of the telegraph.

1816 British chemist William Hyde **Wollaston** built the forerunner of the **reserve battery**. To avoid strong acids eating away the expensive metal plates of his batteries or cells when not in use, he simply hoisted the plates out of the electrolyte, a system copied by many battery makers in the nineteenth century.

1820 Danish physicist Hans Christian **Ørsted** showed how a wire carrying an electric current can cause a nearby compass needle to move. The first demonstration of **the connection between magnetism and electricity** and of the existence of a hitherto unknown, **non-Newtonian force**. Two major scientific discoveries from a simple experiment.

1820 One week after hearing about Ørsted's experiment, French physicist and mathematician André-Marie **Ampère** showed that parallel wires carrying current in the same direction attract eachother, whereas parallel wires carrying current in opposite directions repel eachother.

He also showed that the force of attraction or repulsion is directly proportional to the strength of the current and inversely proportional to the square of the distance between the wires.

He precisely defined the concept of **electric potential** distinguishing it from **electric current**. He later went on to develop the relationship between electric currents and **magnetic fields**.

Ampère's life was not a happy one. Traumatised by his father's execution by the guillotine during the French Revolution, there followed two disastrous marriages, the first one resulting in the early death of his wife. Finally he had to cope with an alcoholic daughter. The epitaph he choose for his gravestone says Tandem Felix ('Happy at last'). The unit of current was named the Ampère in his honour.

1820 French mathematician Jean-Baptiste **Biot**, together with compatriot Felix **Savart** , discovered that the intensity of the **magnetic field** set up by a current flowing through a wire varies inversely with the distance from the wire. This is now known as **Biot-Savart's Law** and is fundamental to modern electromagnetic theory. They considered magnetism to be a fundamental property rather than taking Ampére's approach which treated magnetism as derived from electric circuits.

1820 Johann Salomo Christoph **Schweigger** professor of mathematics, chemist and classics scholar at the University of Halle, Germany built the first instrument for measuring the strength and direction of electric current. He named it the "**Galvanometer**" in honour of Luigi **Galvani** rather than a "Schweiggermeter"???. Galvani was in fact unaware of the concepts of current flows and magnetic fields.

1820 Dominique François Jean **Arago** in France demonstrated the first **electromagnet**, using an electric current to magnetise an iron rod.

1820 American chemist Robert **Hare** developed **high current galvanic batteries** by using **spiral wound electrodes** to increase the surface area of the plates in order to achieve the high current levels used in his combustion experiments. He also used such batteries in 1831 to enable blasting under water.

Hare also developed an apparatus he called the Spiritoscope, designed to detect fraud by Spiritualist mediums, and in the process of testing his machine, he became a Spiritualist convert and eventually became one of the best known Spiritualists in the USA.

1821 Prussian physicist Thomas Johann **Seebeck** discovered accidentally that a voltage existed between the two ends of a metal bar when one end was cooled and the other heated. This is a **thermoelectric effect** in which the potential difference depends on the existence of junctions between dissimilar metals (in this case, the bar and the connecting wire used to detect the voltage). Now called the **Seebeck effect**, it is the basis of the **direct conversion of heat into electricity** and the **thermocouple**. See also the **Peltier effect** discovered 13 years later which is the reverse of the Seebeck effect.

Batteries based on the Seebeck effect were introduced by **Clamond** in 1874 and **NASA** in 1961.

1821 The English scientist Michael **Faraday** was the first to conceive the idea of a **magnetic field** which he demonstrated with the distribution pattern of iron filings showing **lines of force around** a magnet. Prior to that, electrical and magnetic forces of attraction and repulsion had been thought to be due to some form of **action at a distance**.

In 1821 Faraday made the first **electric motor**. It was a simple model that demonstrated the principles involved. See **diagram**. Current was passed through a wire that was suspended into a bath of mercury in the centre of which was a vertical bar magnet. The mercury completed the circuit between the battery and the wire. The current interacting with the magnetic field of the magnet caused the wire to rotate in a circular path around the magnetic pole of the magnet. This was the first time that electrical energy had been transformed into kinetic energy. In 1837 **Davenport** made the first practical motor but it did not achieve commercial success and for forty years after Faraday's original invention the motor remained a laboratory curiosity with many wierd and wonderful designs. Typical examples are those of **Barlow** (1922) and **Jedlik** (1928).

This invention was the source of a bitter controversy with Humphry **Davy** and William Hyde **Wollaston** who had tried unsuccessfully to make an electric motor. Faraday was unjustly accused of using Wollaston's ideas without acknowledging his contribution. The upshot was that Faraday withdrew from working on electromagnetics for ten years concentrating instead on chemical research.

Consequently it was not until 1831 that Faraday invented a **generator** or dynamo to drive the motor. Surprisingly nobody else in the intervening ten years thought of it either. Faraday had shown that passing a current through a conductor in a magnetic field would cause the conductor to move through the field but nobody at the time thought of reversing the process and moving the conductor through the field (or conversely moving a magnet through a coil) to create (induce) a current in the conductor.
In an ideal electrical machine, the energy conversion from electrical to mechanical is reversible. Applying a voltage to the terminals of a motor causes the shaft to rotate. Conversely rotating the shaft causes a voltage to appear at the terminals, thus acting as a generator. It was not until 1867 that the idea of a reversible machine occurred to Werner **Siemens** and practical motor-generators were not realised until 1873 by **Gramme** and **Fontaine**.

Faraday, the Father of Electrical Engineering, was a humble man with no formal education who started his career as an apprentice bookbinder. Inspired by the texts in the books with which he worked and with tickets given to him by a satisfied customer, he attended lectures in 1812 given by the renowned chemist, Sir Humphry **Davy**, at the **Royal Institution**. At each lecture Faraday took copious amounts of notes, which he later wrote up, bound and presented to Davy. As a consequence Faraday was taken on by Davy as an assistant for lower pay than he received in his bookbinding job. During his years with Davy he carried out much original work in chemical research including the isolation new hydrocarbons but despite his achievements he was treated as a servant by Davy's wife and by Davy who became increasingly jealous of Faraday's success. Davy also opposed Faraday's 1824 application for fellow of Royal Society when he himself was president. Davy died prematurely in 1829 it is said from inhaling many of the gases he discovered or investigated.

Faraday went on to eclipse his mentor discovering **electrical induction**, inventing the electric **motor**, the **transformer**, the **generator** and the **variable capacitor** and making major contributions in the fields of **chemistry** and the theoretical basis of **electrical machines**, **electrochemistry** , **magneto-optics** and **capacitors**. His inventions and theories provided the foundations of the modern electrical industry but

Faraday never commercialised any of his ideas concentrating more on teaching. He was perhaps the greatest experimenter of his time and although he lacked mathematical skills, he more than made up for it with his profound intuition and understanding of the underlying scientific principles involved which he was able to convey to others. He used his public lectures to explain and popularise science, a tradition still carried on in his name by the IEE today.

Although he was noted for his many inventions, Faraday never applied for a patent.

In 1864 he was offered the presidency of the Royal Institution which he declined. Not so well known is his relationship with **Ada Lovelace** who idolised him and pursued him over a period of several months in 1844 writing flattering and suggestive letters to which he replied, however in the end he did not succumb to her charms.

When the British Prime Minister asked of Faraday about a new discovery, "What good is it?", Faraday replied, "What good is a new-born baby?"

Saint Michael? - Among Victorian scientists and experimenters, Faraday is revered for his high moral and ethical standards. A deeply religious man, he overcame adversity to become one of the nineteenth century's greatest scientists and an inspiring teacher commanding admiration and respect, but he was not entirely beyond criticism. In 1844 a massive explosion in the coal mine of the small Durham mining village of Haswell killed 95 men and boys, some as young as 10 years old: - most of the male population of the village. The mine owners would accept no responsibility for the disaster and the coroner refused to allow any independent assessor to enter the mine. Incensed, the local villagers took their grievance all the way to the Prime Minister, **Sir Robert Peel**. Such was the national concern that Peel dispatched two eminent scientists to investigate, Faraday the "government chemist" and **Sir Charles Lyell** the "government geologist". Their verdict was "Accidental death" and, pressurised by the coroner, they added "No blame should be attached to anyone". In the days before social security, the consequences of this verdict were destitution for the bereaved families.

Faraday's biographers who mention the **Haswell mining disaster** usually only recount the story that Faraday conducted the proceedings while seated on a sack which, unknown to him, was filled with gunpowder.

1822 English mathematician Peter **Barlow** built an **electric motor** driven by continuous current. It used a solid toothed disc mounted between the poles of a magnet with the teeth dipping into a mercury bath, similar in principle to the **Faraday disk**. Applying a voltage between the shaft and the mercury caused the disc to rotate, the contact with the moving teeth was provided by the mercury.

1823 Johann Wolfgang **Döbereiner** discovered that hydrogen gas "spontaneously" ignited in the oxygen of the air when it passes over finely spread metallic platinum. He used the phenomenon, an example of what we now call **catalysis** although he was not aware of it, in the design of a "Platinum Firelighter".

1824 Pure **Silicon** first isolated by **Berzelius** who thought it to be a metal while **Davy** thought it to be an insulator.

1824 While steam engines were still in their infancy, twenty eight year old French physicist and military engineer, Nicolas Léonard Sadi **Carnot** published *"Réflexions sur la Puissance Motrice du Feu"* ("Reflections on the Motive Power of Fire") in which he developed the concept of an idealised heat engine: the first theoretical treatment of heat engines. He pointed out that the efficiency of a heat engine depends on the temperature difference of the working fluid before and after the energy conversion process. This was later stated as:

$$\eta = (T_h - T_c)/T_h \quad \text{or} \quad \eta = 1 - T_c/T_h$$

where η is the maximum efficiency which can be achieved by the energy conversion, T_h is the input (hot) temperature of the working fluid in degrees Kelvin and T_c is its output (cold) temperature. This became known as **Carnot's Efficiency Law** and still holds good today for modern steam turbines and geothermal energy conversion. Carnot also showed that in a reversible process some energy would always be lost providing an early insight into the **Second Law of Thermodynamics**.

1825 **Ampère** quantified the relationship between **electric current** and the changing **magnetic field** that produces it, now known as **Ampère's Law**, and laid the foundation of **electromagnetic theory**. Ten years later **Gauss** derived an equivalent equation for electric fields.

1825 British electrician, William **Sturgeon** credited with inventing the first practical **electromagnet** (5 years after **Arago**), a coil, powered by a single cell battery, wrapped around a horseshoe magnet. The world's first controllable electric device.

1825 To view electrical discoveries in the context of other key events in the **Industrial Revolution**, it was in this year that the Stockton and Darlington Railway, the world's first public railway was opened with George **Stephenson** at the controls of his **steam engine** the **Locomotion** pulling 36 wagons - twelve carrying coal and flour, six for guests and fourteen wagons full of workmen. Five years later in 1930 Stephenson's **Rocket** was successful at the Rainhill trials and was adopted as the engine for the new Liverpool Manchester railway starting a frenzy of railway building - revolutionising the transport of goods, changing the patterns of industrial development, bringing travel within the possibility of the masses and with it - new aspirations.

1826 Italian physicist Leopoldo **Nobili** together with fellow Italian Macedonio **Melloni** developed a **thermoelectric battery** based on the **Seebeck effect**, constructed from a bank of **thermocouples** each of which provided a very low voltage of about 50 milliVolts. Nobili also invented a very sensitive **astatic galvanometer** which compensated for the effect of the earth's magnetic field. The pointer was a compass needle suspended on a torsion wire in the current carrying coil. A second compass needle outside of the coil compensated for any external fields.

1826 German physicist and chemist Johann Christian **Poggendorff** invented the **mirror galvanometer** for detecting an electric current.

1827 German physicist Georg Simon **Ohm** discovered the relationship between voltage and current, V=IR, in a conductor which is now called Ohm's Law. The importance of this relationship lies less in the simple proportionality but on Ohm's recognition that Voltage was the driver of current.

1827 Scottish botanist Robert **Brown** studying the suspension of pollen in water, observed the random movement of the grains we now call **Brownian Motion**. These random movements which were later quantified using statistical methods are also typical of the movement of electrons and ions in an electrolyte. This causes of this phenomenon were eventually explained in 1905 by Albert **Einstein** using the kinetic theory of gases.

1828 Berzelius compiled a table of relative **atomic weights** for all known elements and developed the system of symbols and formulas for describing chemical actions.

1828 Self taught English mathematician George **Green**, who worked in his family's windmill till the age of forty, published in a local journal in Nottingham with only 51 subscribers, mostly family and friends, An Essay on the Application of **Mathematical Analysis to the Theories of Electricity and Magnetism**. It earned him a place at Cambridge as a mature student but its full importance was not recognised at the time until it was rediscovered by William Thomson (later Lord **Kelvin**) just after his graduation in 1845. Kelvin recognised this as a seminal influence in the development of electromagnetic theory.

1828 French physiologist and biologist René Joachim Henri **Dutrochet** discovers **osmosis** - the diffusion of a solvent through a **semi permeable membrane** from a region of low solute concentration to a region of high solute concentration. The semi permeable membrane is permeable to the solvent, but not to the solute, resulting in a chemical potential difference across the membrane which drives the diffusion. Thus the solvent flows from the side of the membrane where the solution is weakest to the side where it is strongest, until the solution on both sides of the membrane is the same strength equalising the chemical potential on both sides of the membrane.

Semi permeable membranes are now widely used as separators in batteries and fuel cells allowing the passage of certain ions while blocking others.

1828 Hungarian priest and physicist of Slovak origin, Ányos **Jedlik** built the first direct current **electric motor** using an electromagnet for the rotor and a **commutator** to achieve unidirectional rotation. Jedlik's motor was a shunt wound machine in which a moving electromagnet rotated within a fixed coil, the reverse of modern conventional motors. The wires powering the electromagnet protruded into two small semicircular mercury cups on either side of the shaft. This provided the required commutation as the wires picked up the current from alternate cups as the shaft rotated. Like many motors at the time, it had no practical application, however in 1855 Jedlik built another motor based on similar principles which was capable of carrying out useful work.

In 1861 he demonstrated a **self excited dynamo** but he did not publish his work. Subsequently **Siemens, Varley** and **Wheatstone** were credited with the invention.

Jedlik continued working on **high voltage generators** and spent his last years in complete seclusion at the priory in Györ.

1829 Nobili invents the **thermopile**, an electrical instrument for measuring **radiant heat** and **infra red radiation**. It was also based on the **Seebeck effect** as in Nobili's thermoelectric battery of three years earlier and consisted of a sensor made up from a bank of thermocouples connected in series which generated an electrical current in response to the heat radiation input. The current was measured by an **astatic galvanometer**, of Nobili's own design. With improvements from **Melloni**, it found extensive use in nineteenth century laboratories.

1829 French physicist Antoine-César **Becquerel**, father of a **dynasty** of famous scientists, developed the **Constant Current Cell**. The forerunner of the **Daniell cell**, it was the first **non-polarising battery**, maintaining a constant current for over an hour unaffected by **polarisation**. It was a two electrolyte system with copper and zinc electrodes immersed in copper nitrate and zinc nitrate electrolytes respectively, separated by a semi permeable membrane. It was left to Daniell to explain how it worked and thus to get credit for the idea.

1830 The **thermostat** made from a **bi-metallic strip**, usually brass and copper, invented by Andrew **Ure** a Glasgow chemistry professor. It did not find much use for 70 years until the advent of electricity supplies to the home when it could be used to operate a switch.

1830 Joseph **Henry** in the USA worked to improve electromagnets and was the first to superimpose coils of wire wrapped on an iron core. It is said that he insulated the wire for one of his magnets using a silk dress belonging to his wife. An early example of **insulated wire**. In 1830 he observed electromagnetic (mutual) **induction** between two coils and his demonstration of **self-induction** predates Faraday, but like much of his work, he did not publish it at the time. An unfortunate tendency which he lived to regret. (See 1835 **Morse**)
The unit of Inductance the Henry is named in his honour.

1831 Faraday invented the **solenoid** and independently discovered the principle of **Induction** and demonstrated it in an **induction coil** or **transformer**. The induction coil has since been "invented" by many others (See 1886 William **Stanley**). Faraday was the first to generate electricity from a magnetic field by pushing a magnet into a coil. He put this to practical use with his invention of the **generator** or **dynamo**, unshackling the generation of electricity from the battery. Faraday's dynamo, named the **Faraday Disk** after its construction, consisted of a copper disk rotating between the poles of a magnet. Current is generated along the radius of the disk where it cuts the magnetic field and is extracted via brushes contacting the shaft and the edge of the disk. See **diagram**. The Faraday Disk functions equally well as a motor and although the machine is said to be unique in that it is a direct current machine which does not need a commutator, it does owe something to **Barlow**'s 1922 toothed motor design. (See also **Siemens** 1867).

From his experiments Faraday defined the relationship now known as **Faraday's Law of Induction** which states that the magnitude of the emf induced in a circuit is proportional to the rate of change of the magnetic flux that cuts across the circuit. It was left to **Maxwell** to express Faraday's Law and his notions of **Lines of Force** in mathematical terms.

1831 Henry demonstrated a simple **telegraph** system sending a current through a mile and a half of wire to trigger an electromagnet which struck a bell (thereby inventing the **electric bell**, for many years the main domestic use of the battery). He used a simple coding system switching the current on and off to send messages down the line. Henry thought that patents were an impediment to progress and like Faraday he believed that new ideas should be shared for the benefit of the community. He subsequently freely shared his ideas on telegraphy with S. F. B. **Morse** who however went on to patent them passing them off as his own.

1831 -1835 Henry developed the **relay** which was used as an **amplifier** rather than as a switch as it is used today. At the end of each section, the feeble current would operate a relay which switched a local battery on to the next section of the line renewing the signal level. This enabled signals (currents) to be carried (relayed) over long distances making possible **long distance telegraphy**. In fact the relay reconstituted the signal rather than amplified it, just as the repeaters used in modern digital circuits do, thus avoiding amplifying the noise. The relay and its use with local battery power to "lengthen the telegraph line" were more of Henry's ideas which he failed to publicise or exploit.
Henry was appointed the first Secretary of the **Smithsonian Institution** when it was founded in 1846.

For over thirty years telegraphy was the main practical application of the battery, this new found electrical technology.

1832 After witnessing a demonstration of von Sömmering's **electrochemical telegraph** some time earlier, **Baron Schilling** an attaché at the Russian embassy in Munich, in turn developed the idea by making an **electromagnetic device** which he demonstrated in 1832. It was a **six wire system** which used the movement of five magnetic needles to indicate the transmission of a signal. This was the method subsequently used by Cooke and Wheatstone who later "invented" and patented the **five needle electric telegraph** for two way communications in **1837**.

1832 Hippolyte **Pixii** built his "magneto generator" the first practical application of Faraday's **dynamo**. The term "**magneto**" means that the magnetic force is supplied by a permanent magnet. His first machine rotated a permanent magnet in the field of an electromagnet generating an **alternating current** for which there was no practical use at the time. The following year at **Ampère**'s suggestion he added a **commutator** to reverse the direction of the current with each half revolution enabling unidirectional - **direct current** to be produced. Pixii's magneto liberated electrical experimenters from their dependence on batteries.

1833 Faraday published his quantitative Laws of **Electrolysis** which express the magnitudes of electrolytic effects and **galvanic reactions**, putting Volta's discoveries and battery theory on a firm scientific basis.

- The amount of a substance deposited on each electrode of an electrolytic cell is directly proportional to the quantity of electricity passed through the cell.
- The quantities of different elements deposited by a given amount of electricity are in the ratio of their chemical equivalent weights.

With William **Whewell**, he also coined the words, **electrode, electrolyte, anode** (Greek - Way in)**, cathode** (Greek - Way out) and **ion** (Greek - I go) .

1833 Samuel Hunter **Christie** of the British Royal Military Academy publishes a bridge circuit for comparing or determining resistance, later to be called the Wheatstone Bridge.

1833 German physicist Wilhelm Eduard **Weber**, working with Gauss, demonstrated "the world's first **electric telegraph**" operating over a distance of 3 kilometers. One of many such claims before and since. The system used a simple coding scheme switching the current on and off, similar to Henry's, combined with reversing the polarity of the current to deflect a compass needle in opposite directions, to send different letters down a single wire. Over the subsequent years Weber investigated terrestrial and induced **magnetic fields** and verified the theoretical laws put forward by Ampère and others using **electrical instruments** which he designed for this purpose. The unit of Magnetic Flux is named the Weber in his honour.

1833 Russian physicist Heinrich Friedrich Emil **Lenz** formulated **Lenz Law** which states that an induced electric current flows in a direction such that the current opposes the change that induced it. A special case of the Law of Conservation of Energy. The law explains that when a conductor is pushed into a strong magnetic field, it will be repelled and that when a conductor is pulled out of a strong magnetic field that the magnetic forces created by the induced currents will oppose the pull. This also explains the phenomenon of **back emf** in electric motors, that is, the voltage created by the moving armature which opposes the applied voltage and hence the movement of the armature itself. Lenz law was later extended for more general application by Le Chatelier.

In the same year he also showed that the resistance of a metal increases with temperature.

1833 Scottish chemist Thomas Graham discovers the rate at which a gas diffuses is inversely proportional to the square root of the density of the gas. Now known as **Graham's Law of Diffusion**. Diffusion however is not confined to gases, it can take place with matter in any state. It may take place through a semi permeable membrane, which allows some, but not all, substances to pass. In solutions, when the liquid solvent passes through the membrane but the solute (dissolved solid) is retained, the diffusion process is called **osmosis**, a process which is used in many battery designs.

1834 French clockmaker Jean Charles Athanase **Peltier** discovered that when a current flows through a closed loop made up from two dissimilar metals, heat is transferred from one junction between the metals to the other and one junction heats up while the other cools down. Used as the basis for **refrigeration** products with no moving parts. This is now known as the **Peltier effect** and is the reverse of the **Seebeck effect** discovered 13 years earlier.

1835 German mathematician Carl Friedrich **Gauss** quantified the relationship between the **electric flux** flowing out a closed surface and the **charge** enclosed in the surface. Now know as **Gauss's Law** it is the **electrical field** equivalent of **Ampère's Law** for magnetic fields. It was not published however until 1867.
Gauss also did pioneering work on probability and statistics, defining and characterising the **Normal Distribution**, now also named the **Gaussian Distribution** in his honour. It is the theoretical basis of much of today's **quality control** of which **Six Sigma** is an example.

Gauss was one of the worlds most gifted and prodigious mathematicians making major contributions to geometry, algebra, statistics, probability theory, differential equations, electromagnetics, and astronomy. Working alone for much of his life Gauss' personal life was, like Ampère's, tragic and complicated. His first wife died early, followed by the death of one of his sons, plunging him into a depression which was not helped by an unhappy second marriage which also ended with the early death of his second wife.

While he was working, when informed that his wife is dying Gauss replied: "Ask her to wait a moment - I am almost done. "

1835 Samuel Finley Breese **Morse**, American artist and professor of the Literature of the Arts of Design in the University of the city of New York and religious bigot with a mandate directly from God, made a career change at the late age of 41and started work on telegraphy. Undaunted by his lack of knowledge of the principles of electricity, he sought the assistance in developing his ideas, first from a colleague Leonard **Gale** of the University of New York who pointed out to Morse the need for insulation on the windings of his electromagnets, and then from Joseph **Henry** who already had a working telegraph system and who explained the need for **relays** to extend the range of the system. Morse subsequently patented Henry's ideas in his own name. He demonstrated the "first" **electric telegraph** in 1835 ignoring many prior claims dating as far back as **Gray** in 1729, **Morrison**'s design of 1753 and **Salvá**'s in 1804 as well as more practical recent inventions by **Henry** in 1831 and **Weber** in 1833.
Morse patented his system in 1837 and although it came after the **needle telegraphs** of **Schilling** (1832) and that of **Cooke and Wheatstone** (1837) which was patented earlier the same year as Morse's, Morse's system was simpler and more robust using only a single signalling wire plus a return wire and its use spread very quickly.

Morse subsequently claimed sole authorship for these ideas and also for the relay, another of Henry's inventions ignoring Henry's essential contributions to the system thus creating an irreparable rift with Henry. Similarly, the coding system **Morse Code** on which single channel telegraphy depends was based on existing technology including Henry's ideas, as well as those of **Gauss** and **Weber**, which Morse developed jointly with Albert **Vail**, Morse's business partner. It was Vail who invented the Morse key and also the printing telegraph which was patented in Morse's name. Their relative contributions are still in dispute. (See also 1841 **Bain**)
Henry is reported to have said in later life "If I could live my life again, I might have taken out more patents".

For 35 years the battery was a solution looking for a problem. It had been used on a small scale as a laboratory tool providing the energy for electrolysis in the analysis of chemical compounds and the isolation of new elements but it was Morse's electric telegraph which eventually created the **deployment of batteries** on an industrial scale.

1835 Electric arc welding proposed by James Bowman **Lindsay** of Dundee. The idea was eventually patented fifty years later by **Benardos** and **Olszewski** in 1885.
Lindsay had many bright ideas, including the design for an **electric light** which he demonstrated in 1836 and several innovations in the field of **telegraphy** but none of these were ever commercialised.

1836 Demonstration by a British chemist John Frederic Daniell of the **Daniell cell**, a **two electrolyte system** using two electrodes immersed in two fluid electrolytes separated by a porous pot.
Volta's simple voltaic cell cannot operate very long because bubbles of hydrogen gas collect at the copper electrode acting as an insulator, reducing or stopping further electron flow. This blockage is called **polarisation**. Daniell's cell overcomes this problem by using electrolytes which are compatible with the electrodes. Thus the zinc electrode is suspended in an electrolytic solution of zinc sulphate which is contained in the porous pot (Initial designs used sulphuric acid rather than zinc sulphate). The porous pot is in turn immersed in the copper sulphate solution which is contained in a glass jar into which the copper electrode is also suspended. The Daniell cell does not produce gaseous products as a result of galvanic action and copper rather than hydrogen is deposited on the cathode. Daniell's **non-polarising** battery was thus able to deliver sustained, constant currents, a major improvement on the Voltaic pile.
The Daniell cell chemistry was also available in other configurations which provide superior performance such as the **gravity cell** or **crowfoot cell** which eliminated the porous pot.
Daniell's cell was however based on a similar non polarising battery design demonstrated by **Becquerel** in 1829 which used nitrate electrolytes rather than the sulphate electrolytes used by Daniell. Despite the prior art, Daniell, rather than Becquerel, is remembered as the inventor of the non-polarising cell.

Early galvanic cells were all based on **acidic electrolytes** and many of these designs produced hydrogen at the cathode causing the cell to become polarised. Two approaches were adopted to solve the polarisation problem. Daniell's solution was a **non-polarising cell** which did not produce hydrogen. The other alternatives were **depolarising cells** containing oxidising compounds which absorbed the hydrogen as it was produced and did not allow the build up of bubbles. The Leclanché cell which uses manganese dioxide as a depolariser is an example of this type.

1836 Although it had been known for many years that some chemical processes could be speeded up by the presence of some unrelated chemical agent which was not consumed by the chemical action and that the phenomenon had been used by Döbereiner and others, it was Berzelius who in 1836 introduced the term **catalyst** and elaborated on the importance of **catalysis** in chemical reactions.

1836 Electric light from batteries shown at the Paris Opera.

1836 Parisian craftsman Ignace **Dubus-Bonnel** was granted a patent for the spinning and weaving of glass. His application was supported by a small square of woven **fibreglass**. The drawn glass was kept malleable by operating in a hot vapour bath and weaving was carried out in a room heated to over 30°C.

1836 Irish priest, scientist, and inventor, Nicholas Joseph **Callan**, working at Maynooth Theological University in Ireland, invented of the induction coil. He discovered that by interrupting a low current through a small number of turns of thick copper wire making up the primary winding of an **induction coil**, a very high voltage could be induced across the terminals of a high turns secondary winding of thinner copper wire on the same iron core. Such induction coils are used in the automotive industry to operate the sparking plugs, but in the other industries they are generally known as **Ruhmkorff coils**.
The importance of Callan's pioneering work was not recognised at his remote institution which had other priorities and he never received recognition for this invention which is now associated with the name of German-born Parisian instrument maker, Heinrich Ruhmkorff. Like all instrument makers, he put his name on every instrument he made and Callan's coil eventually become known as the "Ruhmkorff Coil".
Callan also developed a galvanic cell known as the Maynooth Battery in 1854.

1837 Faraday discovers the concept of **dielectric constant**, invents the **variable capacitor** and states the law for calculating the capacitance. The unit of **Capacitance** the Farad is named in his honour.

1837 Sixteen years after the principle was demonstrated by Faraday, self taught American blacksmith Thomas **Davenport** patented the first practical **electric motor** as "an application of magnetism and electro-magnetism to propelling machinery." Powered by a galvanic battery consisting of a bucket of weak acid containing concentric cylindrical electrodes of dissimilar metals, the motor was a shunt wound, brush commutator device. The magnetic field of the stator was provided by two electromagnets. Two further electromagnets formed the spokes of a wheel which acted as the rotor. The commutator reversed the polarity of the rotor electromagnets as they passed the alternate north and south poles of the stator to create unidirectional rotation. It was granted the first ever patent for an electrical machine.

Davenport's "revolutionary" invention was ahead of its time and it did not bring him the commercial success his efforts deserved. At the time, the lack of suitable batteries or any other source of electrical power to drive the motor inhibited its adoption and his persevering endeavours to improve and promote the motor led him into bankruptcy. His pioneering use of electromagnets in both the stator and the rotor of his machine went largely unnoticed until the idea was reinvented simultaneously by **Varley, Siemens** and **Wheatstone** in 1866 for use in their designs for dynamos. It was not until forty years after Davenport's invention that the demand for electric motors eventually took off. Unfortunately Davenport didn't live to see it. He died aged 49 in 1851.

1837 Patent granted for a **Needle electric telegraph** (**Two way electric communications**) conceived by William Fothergill **Cooke**, a retired English surgeon of the Madras army studying anatomy at the University of Heidelberg, and refined by physicist **Sir Charles Wheatstone** of King's College, London. (See 1816 **Ronalds**) This was claimed to be the first practical battery powered telegraph, however it is very similar to **Schilling**'s design of 1832. An elegant design, instead of using one wire for each letter it used only five signalling wires plus a return wire. By using a combination of the five signalling needles the number of wires could be reduced. When activated, the needles pointed to individual letters on a board. Twenty different letters could be identified by only five wires. There was no provision for sending the letters C, J, Q, U, X and Z. The design was overtaken by the simpler single wire system devised **Morse** using his coding system of dots and dashes. The relationship between Cooke and Wheatstone eventually ended acrimoniously over a dispute about their respective contributions to the design.

Wheatstone claimed many inventions in his lifetime, usually some time after they had been invented by somebody else. Apart from the **needle telegraph** see the **electric clock** , **punched tape** and the **dynamo**. At least he acknowledged that the **Wheatstone Bridge** was invented by somebody else.

1837 First commercially available **insulated wire** made by British haberdasher W. **Ettrick** who adapted silk wound "millinery" wire, used in hat making, for electrical purposes. The same year William Thomas **Henley** made a six head wire wrapping machine for manufacturing silk insulated wire and founded Henley Cables.

1837 James W. **McGauley** of Dublin invented the **self acting circuit breaker** in which the electric current moved an armature which opened the circuit switching off the current. When the current was removed the armature moved back to its original position and switched on the current once more causing the armature to oscillate and the current to be switched rapidly on and off. The same year American inventor Charles Grafton **Page** built a similar device which he called a **rocking magnetic interrupter**. The original purpose of these devices was to provide current pulses to the primary of an induction coil causing repetitive high voltage sparks at the terminals of the secondary winding. This **trembler** mechanism was subsequently widely used in **electric bells, buzzers and vibrators**.

1838 Scottish engineer Robert **Davidson** built a **DC electric motor** based on iron rotor elements driven by pulses from electromagnets in the stator. It was the first example of what we would now call a **switched reluctance motor**. The motor comprised two electromagnets one on either side of a wooden rotor and three axial iron bars equally spaced around the periphery of the rotor. The electromagnets were switched on and off in turn by means of a mechanical commutator driven from the rotors.
Davidson used four of these motors to drive a 5 ton **electric locomotive** on the newly opened Edinburgh/Glasgow railway in 1842 reaching a speed of 4 mph over a distance of one and a half miles.
The vehicle was powered by two large batteries constructed from wooden troughs each with 20 cells containing sulphuric acid in which were suspended zinc and iron electrodes. The motor speed was controlled by lowering or raising the electrodes into and out of the acid. A resin sealant

protected the wooden cells from attack by the acid.

Like **Davenport**'s motor, Davidson's motor was also ahead of its time and was not developed into a practical product. The more efficient electromagnetic rotors and stators as pioneered by Davenport, became the norm and the reluctance motor was forgotten. It was however revived in the 1960's when new semiconductor technology made electronic commutation possible and, because of its simplicity, the reluctance motor finds many uses today.

1838 Carl August von **Steinheil** a German physicist discovers the possibility of using the "**earth return**" or "**ground return**" in place of the current return wire for the signal in telegraph circuits thus enabling communications using a single wire.

1839 Steinheil builds the first **electric clock**.

1839 Welsh lawyer Sir William Robert **Grove** demonstrates the first **Fuel Cell**. Attempting to reverse the process of electrolysis by combining hydrogen and oxygen to produce water, he immersed two platinum strips surrounded by closed tubes containing hydrogen and oxygen in an acidic electrolyte. His original fuel cell used dilute sulfuric acid because the reaction depends upon the pH when using an aqueous electrolyte. This first fuel cell became the prototype for the Phosphoric Acid Fuel Cell (PAFC) which has had a longer development period than the other fuel cell technologies.

The same year Grove also demonstrated an improved two electrolyte non-polarising galvanic cell using zinc and sulphuric acid for the anodic reaction and platinum in nitric acid for the cathode. Known as the **Grove cell** it provided nearly double the voltage of the first **Daniell cell**. Grove actually developed a **rechargeable cell** however there were few facilities for recharging at that time and the honour for inventing the secondary cell eventually went to **Planté** in 1860. Grove's nitric acid cell was the favourite battery of the early American telegraph systems (1840-1860), because it offered high current output. However it was found that the Grove cell discharged poisonous nitric dioxide gas and large telegraph offices were filled with gas from rows of hissing Grove batteries. Consequently, by the time of the American Civil War, Grove's battery was replaced by the Daniell battery.

In later life (1880) Grove became a high court judge.

1839 The **Magneto hydrodynamic (MHD) Generator** proposed by Michael **Faraday**.

1839 Prussian engineer Moritz Hermann von **Jacobi** financed by Czar Nicholas makes first **electric powered boat** using 128 Grove cells. He also formulated the law known as the **Maximum Power Theorem** or **Jacobi's Law** which states: "Maximum power is transferred when the internal resistance of the source equals the resistance of the load". Also known as **Load matching**.

In 1838 von Jacobi also discovered **electroforming** by which duplicates could be made by **electroplating** metal onto a mould of an object, then removing the mould. This galvanic process was used for making duplicate plates for relief or letterpress printing when it was called **electrotyping**.

1839 Alexandre-Edmund **Becquerel** discovered the **photovoltaic effect** when he was only nineteen while experimenting with an electrolytic cell made up of two metal electrodes placed in an electrically conducting solution. He noticed that small currents were generated between the metals on exposure to light and these currents increased with the light intensity. This new source of electricity never had the same impact as the Volta's cells since the currents were small and the phenomenon was largely ignored by the scientific community. 100 years later Becquerel's discovery was recognised as the first known example of a **P-N junction**. See also **Becquerel 1896**

1839 Polystyrene isolated from natural resin by German apothecary Eduard **Simon** however he was not aware of the significance of his discovery which he called Styrol. Its significance as a **plastic polymer** with a long chain of styrene molecules was recognised by **Staudinger** in 1922.

1840 James Prescott **Joule** an English brewer published "On the Production of Heat by Voltaic Electricity" showing that the heat produced by an electric current is proportional to **I^2R** now known as **Joule's Law**. He also discovered that electrical power generated is proportional to the product of the current and the battery voltage and he established that the various forms of energy, mechanical, electrical, and heat - are basically the same and can be changed, one into another. Thus he formed the basis of the law of **Conservation of Energy**, now called the **First Law of Thermodynamics**.

1840 Robert Sterling **Newall** from Dundee patented a wire rope making machine suitable for manufacturing **undersea telegraph cables**. It was used to make the first successful telegraph cable connecting England and France in 1851 and later with others the first transatlantic telegraph cable. The cable was insulated with **gutta-percha**, the adhesive resin of the isonandra gutta tree, introduced to Europe in 1842 by Dr. William **Montgomerie**, a fellow Scot working as a surveyor in the service of the East India Company. Gutta percha was used for 100 years for cable insulation until it was eventually replaced by **polyethylene** (commonly called polythene) and **PVC**.

1840 Electroplating, a process discovered by **Cruikshank** forty years earlier, was re-invented by the **Elkingtons** of Birmingham and commercialised by Thomas **Prime**. Articles to be plated were suspended as one electrode in a bath containing an electrolyte of silver or gold dissolved in cyanide. When the voltage was applied to the electrodes the metal was deposited on the suspended article.

1840 Eminent British mathematician and Astronomer Royal, George Biddell **Airy**, develops a **feedback device** for continuously manoeuvering a telescope to compensate for the earth's rotation. Problems with his mechanism led to Airy becoming the first person to discuss instability (hunting or runaway) in **closed-loop control systems** and the first to analyse them using differential equations. Stability criteria were later established by **Maxwell**.

Feedback control systems were not new. The list below gives some examples from earlier times:

- **270 B.C.** Greek inventor and barber **Ktesibios** of Alexandria invented a **float regulator** to keep the water level in a tank feeding a **water clock** (the **clepsydra** - Greek water thief) at a constant depth by controlling the water flow into the tank.
- **250 A.D.** Chinese engineer **Ma Chun** invented the **cybernetic machine**, also called the **south pointing carriage**, models of which can be found in several museums throughout the world. Based on connecting the wheels through a system of differential gears to a pointer, usually in the form of a statuette with an outstretched arm, the pointer always points south no matter how far the carriage has travelled or how many turns it has made. Legend has it that a Chinese general used south pointing chariots to guide his troops against the enemy through a thick fog.
- **1620** Dutch engineer living in England Cornelius **Drebbel** invented the **thermostat** for his stove. It depended on the expansion and

contraction of a liquid to move a damper which controlled the air flow to the fire.

- **1745** Scottish blacksmith and millwright Edmund **Lee** added a **fantail** to the moveable cap of the windmill, perpendicular to the main sails, to keep the main sails always pointing into the wind.
- **1749** English clockmaker John **Harrison** used a **bi-metallic strip** to compensate for temperature changes affecting the balance springs in his clocks. As the temperature rises the bi-metallic strip reduces the effective length of the balance spring to compensate for its expansion and change in elasticity.
- **1787** English carpenter Thomas **Mead** regulated the speed of rotation of a windmill using the displacement of a **centrifugal pendulum** to control the effective area of the sails.
- **1788** James **Watt** designed the **centrifugal flyball governor** to control the speed of his steam engines by adjusting the steam inlet valve.

Considering his track record, Airy surprisingly held the post of Astronomer Royal, the highest office in the British civil service, for forty six years. Filled with his own self importance he belittled the work of those whom he considered his social inferiors such as **Faraday** whose mathematics, in his view, wasn't up to scratch and John Couch **Adams** who predicted the existence and orbit of the planet Neptune and whom Airy ordered to proceed slowly and re-do his calculations "in a leisurely an dignified manner". Consequently Airy missed its eventual discovery which was scooped by Frenchman Urbain Jean Joseph **Le Verrier**.

In his role as chief scientific advisor to the government he put a premature end to **Babbage**'s pioneering work on computers with his verdict, "I believe the machine to be useless, and the sooner it is abandoned, the better it will be for all parties", which cut off all government funding for the project.

Airy also advised against the construction of the Crystal Palace to house the Great Exhibition of 1851 because he said the structure would collapse when the salute guns were fired. Despite Airy's objections, it was built anyway and was a great success.

After the Tay Bridge disaster in 1879 when the bridge collapsed into the river during a storm killing all 75 passengers on the train passing over it at the time, the subsequent investigation found that Airy, who who provided the wind loading for designer Thomas **Bouch**, seriously miscalculated the effect of a Tayside gale on the structure, and that the bridge would have fallen "even if construction had been perfect".

1840 "Steam Electricity" , electrostatic discharges produced by the frictional electrification of water droplets, observed by a colliery "Engine Man" near Newcastle in England when probing a steam leak. The phenomenon was investigated by local lawyer, (later to be engineer and arms manufacturer), William George **Armstrong** who constructed what he called a **Hydro-Electric Generator** using the effect to produce electrostatic charges on demand. It consisted of a boiler insulated from the ground generating a jet of steam from which sparks could be drawn on to an insulated metallic conductor. The conductor became positively charged, while the boiler acquired a negative charge.

1841 The non-polarisng **Carbon-Zinc cell**, substituting the cheaper carbon for the expensive platinum used in Grove's cell, invented by German chemist Robert Wilhelm **Bunsen**. His battery found large scale use for powering arc-light and in electroplating.

Bunsen did not invent the eponymous burner for which he is famous. The basic burner was in fact invented by **Faraday** and improved by Peter **Desaga**, a technician working for Bunsen at the University of Heidelburg. The improved burner was designed to provide the high temperature flames needed for Bunsen's joint studies of spectroscopy with Kirchhoff and Desaga was smart enough to manufacture and sell the new device under his boss's name.

Bunsen never married. He was a popular teacher who delighted in working with foul smelling chemicals. Early in his career he lost the use of his right eye when an arsenic compound, cacodyl cyanide, with which he was working, exploded.

1841 Scottish clockmaker Alexander **Bain** invented the first pendulum **electric clock**. Bain demonstrated his clock to Charles **Wheatstone** who copied the clock and three months later demonstrated it to the Royal Society claiming it as his own invention. Fortunately, unknown to Wheatstone, Bain had already patented the invention.
Bain also proposed a method of generating electricity to power his clock by means of an **earth battery**. This consisted of two square plates of zinc and copper, about two feet square, buried deep in the ground a short distance apart forming a battery with the earth acting as the electrolyte. Such an arrangement produces about one volt continuously.

1843 Alexander **Bain** patented a device to scan a two-dimensional surface and send it over wires. Thus, the patent for the **fax machine** and the first use of **scanning** to dissect and build up an image was granted 33 years before the patent was given for the telephone. Over a period of five years Bain designed and patented many improvements to the **electric telegraph** including the use of **punched tape** (re-invented by **Wheatstone** and sold to Samuel **Morse** in 1857) which were widely adopted at the time. Unfortunately he derived no financial benefit from his ideas. His efforts and his money were spent in pursuing patent infringements by Samuel Morse and he retired into a life of obscurity, poverty and hardship.

1843 The first **computer program** was written by Augusta Ada Byron, Countess of Lovelace to calculate values of a Bernoulli function. Known as **Ada Lovelace** she was the beautiful daughter of romantic English poet Lord Byron and wife of the Earl of Lovelace. She was tutored by famous mathematician Augustus **De Morgan** at the University of London and became the world's first **software engineer**. Convinced of her own genius she let everybody know it at every opportunity. She worked as an assistant to Charles **Babbage** on the development of his "analytical engine" the world's first **programmable computer** which used punched cards for input and gears to perform the function of the beads of an abacus.
Before Babbage, computing devices were mostly analogue, performing calculation by means of measurement, Babbage's machine however was digital, performing calculation by means of counting. It is claimed that Ada originated the concept of using **binary numbers**, a practice used in all modern computers, however Babbage's difference engine and more versatile analytical engine were both based on the decimal numbering system. Her notes indicate that she understood and used the concepts of a **stored program**, as well as looping, indexing, subroutine libraries and conditional jumps, the first use of logic in a machine, however the extent of Babbage's contribution to these thoughts and how much was her own work is not clear. She wrote "The Analytical Engine ... weaves algebraic patterns, just as the Jacquard-loom weaves flowers and leaves." Though her contribution to the technology may be questioned, her charm did wonders for Babbage's PR (although it didn't quite work on Michael Faraday).

Ada however managed to run up considerable gambling debts with her lover John Crosse and as a solution she applied her mathematical prowess to fresh fields developing a winning "system" for betting on horses (proving, incidentally, that genius and common sense don't always go hand-in-hand). Unfortunately, the horses being unaware of their responsibilities, the system didn't win and Ada finished her life as a bankrupt, alienated from her family, addicted to laudanum (opium), dying a painful death from cancer of the cervix at the age of 36, repeating the demise of her father, also an opium addict who died of a fever at same age of 36.

Babbage did not have the financial resources to complete his machines and he appealed to the Prime Minister Robert **Peel** for help, but after taking advice from the formidable Astronomer Royal **Sir George Airy**, the request was turned down and his machines were never finished. In 1991 the British Science Museum completed the construction of Babbage's Difference Engine No.2 from Babbage's original drawings with new components and it worked just as he said it would, performing its first test calculation for the public, the powers of seven ($y=x^7$) for the first 100 values.

1843 Sir Charles **Wheatstone** "found" a description of the **Christie**'s 1833 bridge circuit, now known as the **Wheatstone Bridge**, and published it via the Royal Society though he never claimed he invented it.
The same year Wheatstone also invented the **Rheostat** (Greek - "Rheo" Flowing stream) variable resistor.

1843 Patents for the **vulcanisation** of natural rubber with sulphur to improve its strength, wearing properties and high temperature performance were awarded to Thomas **Hancock** in England in May 1843 and one month later to Charles **Goodyear** in the USA. Subsequently patents for hard rubber called **vulcanite** or **ebonite**, created by using excess sulphur during vulcanisation, were granted to Hancock in England in 1843 and to Nelson Goodyear (brother of Charles) in the USA in 1851.
Ebonite is a hard, dark and shiny material initially used for jewellery, musical instruments, decorative objects and dental plates (with pink colouring) for nearly 100 years. It is also a good **insulator** and soon found use in electrical equipment and power distribution panels.
Ebonite was a milestone because it was the first **thermosetting material** and because it involves modification of a natural material.
Ebonite mouldings were exhibited by both Hancock and Goodyear at the Great Exhibition of 1851.

1843 German founder of modern **electrophysiology** Emil **du Bois-Reymond** discovered that **nerve impulses** were a kind of **"electrical impulse wave"** which propagated at a fixed and relatively slow speed along the nerve fibre. In 1849, using a galvanometer wired to the skin through saline-soaked blotting paper to minimise the contact resistance, he was able to detect minute electrical discharges created by the contraction of the muscles in his arms. Realizing that the skin acted as an insulator in the signal path, he increased the strength of the signals by inducing a blister on each arm, removing the skin and placing the paper electrodes within the wounds. He determined that a stimulus applied to the electropositive surface of the nerve membrane causes a decrease in electrical potential at that point and that this "point of reduced potential", or impulse, travels along the nerve like a wave.

Galvani's theory of **animal electricity** vindicated at last? See also **nerve impulses**.

1845 Michael **Faraday** discovers that the plane of polarisation of a light beam is rotated by a magnetic field. The first experimental evidence that light and magnetism are related. Now called the **Magneto-Optic effect** or the **Faraday effect**.

1845 Gustav Robert **Kirchhoff** a German physicist at the age of 21 announced the laws which allow calculation of the currents, voltages, and

resistances of **electrical networks**. In further studies, based on **Kelvin**'s mathematical representation of the **circuit elements**, he demonstrated in 1857 that current flows through a conductor at the **speed of light**.
Kirchhoff formed a productive working partnership with **Bunsen** at the University of Heidelburg where they discovered the that the flames of each element had a unique emission and absorption visible light spectrum, founding the science of emission spectroscopy for analysing and identifying chemical substances. They invented the spectroscope which allowed them to analyse not only earthly elements but also to determine the composition of the sun and the stars by spectral analysis of the radiation they emit.
After an accident in early life, Kirchhoff spent most of his working life in a wheelchair or on crutches.

1846 The **Smithsonian Institution** established in the USA, "for the increase and diffusion of knowledge among men" with a large endowment from English chemist and mineralogist, James **Smithson**, in neat symmetry with the founding of the **Royal Institution** in England by the American, Count **Rumford**. Joseph **Henry** was chosen as the Smithsonian's first distinguished Secretary. Smithson never visited the United States but after he died his remains were brought there for burial.

1846 From his experiments on magneto optics **Faraday** discovered that some substances such as heavy glass and Bismuth are repelled rather than attracted by magnets and named the phenomenon diamagnetism. Using the analogy with dielectrics and conductors he made the distinction between **diamagnetics** - "poor conductors of magnetic force" and **paramagnetics** - "good conductors of magnetic force".

1848 Scottish physicist, born in Belfast, William **Thomson** (later Lord **Kelvin**) established the basis for an absolute temperature scale. Starting from the experimental results of **Charles** and **Gay Lussac**, Kelvin showed also that there is an absolute zero of temperature which is -273°C. The absolute temperature scale is named the Kelvin scale in his honour and -273°C is called 0°K or absolute zero.

Kelvin was an infant prodigy in mathematics, entering Glasgow University at the age of ten, he started the undergraduate syllabus when he was only fourteen and published his first scholarly papers, correcting errors in the works of both **Fourier** and Fourier's critics, when he was only sixteen. Fourier remained an inspiration to him throughout his early years. Kelvin always sought practical analogies to explain his theories and published over 600 scientific papers on mathematics, **thermodynamics**, **electromagnetics**, **telecommunications**, hydrodynamics, oceanography and **instrumentation** and he filed 70 patents. He is remembered for his work on the **Transatlantic Telegraph Cable** but he initially gained fame by estimating the age of the earth from a knowledge of its cooling rate at over 100 million years (later revised and broadened from 20 to 400 million years) in contradiction of the prevailing religious, creationist view of the world. Despite this he maintained a strong and simple Christian faith throughout his life and engaged in a long running public disagreement with Charles **Darwin**, remaining "on the side of the angels", claiming that, according to his calculations, the age of the earth was too short for Darwin's evolutionary changes to have taken place. (Current estimates give the age of the earth as 4.6 billion years taking into account the heating effect of radioactivity of the earth's core, something of which Kelvin could not have been aware). He remained actively involved in scientific work until he was 75 but in later life he found it difficult to accept **Maxwell's theories**, for which he himself had been the Genesis, and the concept of **radioactivity**.

According to C Watson, Kelvin's biographer, "During the first half of Thomson's career he seemed incapable of being wrong while during the second half of his career he seemed incapable of being right."

1849 The first accurate terrestrial measurement of the **speed of light** was made by French physicist Armand Hippolyte Louis **Fizeau**. Previous measurements had been based on observations of the movement of planets and moons by Danish astronomer Ole Christensen **Rømer** (1676), English astronomer James **Bradley** (1728) and others. Fizeau directed a beam of light through the gaps in a rotating cog wheel to a mirror several miles away and observed the reflection of the pulses of light coming back through gaps in the wheel. Depending on the speed of rotation of the wheel, the returning light would either pass though the gap or be blocked by a tooth. The speed of light could be calculated from the distance to the mirror, the number of teeth on the wheel and its rate of rotation. He determined the speed of light to be 186,000 miles per second or 300,000,000 metres per second.
Also known as **Einstein's constant**, the speed of light is represented by the symbol **c** for "celeritas" (Latin - "speed").

1849 The **Bourdon tube pressure gauge** was patented by French engineer Eugene Bourdon. It is still one of the most widely used instruments for measuring the pressure of liquids and gases of all kinds, including steam, water, and air up to pressures of 100,000 pounds per square inch as well as pressures below atmospheric. It consists of a "C" shaped or spiral curved tube sealed at one end which tends to straighten out when a pressurised fluid is admitted into it. The displacement of the end of the tube is used to move a pointer or other indicator.

1850 Prussian born theoretical physicist Rudolf Julius Emmanuel **Clausius** publishes his seminal paper "On the Mechanical Theory of Heat" establishing the study of **Thermodynamics** and outlining the basis of the Second Law.

1850 The **trembler electric bell** invented by John **Mirand**.

1851 In his treatise "On the Dynamical Theory of Heat." **Kelvin** formally states the **Second Law of Thermodynamics**, that "Heat does not spontaneously flow from a colder body to a hotter". It was later restated in the form "In a closed system **entropy** can only increase", recognising the concept of entropy proposed by Clausius in 1865.

1851 German inventor Heinrich Daniel Ruhmkorff patents the **Ruhmkorff Induction Coil** capable of producing sparks 30 centimetres long. Basically a high turns ratio transformer, it was invented in 1836 by Irish priest Nicholas **Callan**.

1852 English chemist Edward **Frankland** invented the notion of **chemical bond** and introduced the idea of **valency**, that an atom of one element could only compound with a definite number of atoms of another element.

1852 **Joule** and **Kelvin** (William Thomson) discovered that when a gas is allowed to expand without performing external work, the temperature of the gas falls. Now known as the **Joule-Thomson Effect**, it is the basis of nearly all modern refrigerators and gas liquefaction processes. (The **Peltier Effect** is also used in some special cooling applications)

1852 American engineers William F. **Channing** and Moses Gerrish **Farmer** installed the first municipal electric **fire alarm system** using a series of **electric bells** and call boxes with **automatic signaling** to indicate the location of a fire in Boston, twenty four years before the advent of the telephone.

Farmer was a prolific inventor in the same mould as Edison. In the same year (1852) he also demonstrated **diplex** telegraphy, the simultaneous transmission of two signals in the *same direction* down a wire (or channel), the first example of **time division multiplexing (TDM)**. It was based on two rotating switches, one at each end of the line which connected the transmission line alternately to each transmitter / receiver pair permitting sequential, interleaving of signals from each channel. Unfortunately he was not able to develop it into a practical system because of the difficulty of synchronising the receivers with the transmitters, a problem which was not solved until 1874 by **Baudot**.
In 1858 he did however patent a two battery **duplex** system similar to **Gintl's** 1853 design. (See next). As with the diplexer, there were obstacles to overcome before practical duplexers were ready for roll out. In this case it was the design by **Stearns** in 1872 which took the honours.

In 1853 Farmer also patented an **improved battery**.

1853 The **electric burglar** alarm patented by American Minister Augustus Russell **Pope**. When a door or window was opened, it closed an electrical contact initiating an alarm. The rights to the patent were purchased by Edwin **Holmes** who began manufacturing and selling the alarms in 1858 and was subsequently credited with its invention.

1853 Austrian telecommunications engineer Julius Wilhelm **Gintl** working in Vienna, invented a method of **duplex** telegraphy, the simultaneous transmission of two signals in *opposite directions* down a wire (or channel). The first telecommunications duplexer - allowing simultaneous message transmission and reception. It was a two battery, "compensating" system with differential relays, in which two samples of the transmitted signal were arranged to cancel eachother in the local receiving relay but were able to operate the remote receiving relay normally.
In 1855 German engineer Carl **Frischen** working for Siemens & Halske registered of a patent for a simplified version of Gintl's design with only one compensating battery.

1853 Almost 200 years after **Newton**, Scottish engineer William John Macquorn **Rankine** introduced the concept of **potential energy** for stored energy (In mechanical terms - energy based on position). Together with **Kelvin** they applied the concept to **electrical potential** whose unit of measurement they named the **volt**.

1853 Mathematical representation of the **voltage-current relationships** of **capacitors** ($i = C\, dv/dt$) and **inductors** ($v = L\, di/dt$) derived by **Kelvin** enabling the analysis of **RLC circuits** and the performance of telegraph cables. A more detailed model of the cable or transmission line, based on Kelvin's theory, but taking into account the distribution of the capacitance and inductance along the line, was developed by **Kirchhoff** in 1857.

1854 The fundamental idea of the **electrical transmission of sound** (the telephone) was published in the magazine "L'Illustration de Paris" by Belgian experimenter Charles **Bourseul**, working in France.

1854 Heinrich **Geissler**, a master glassblower in Bonn, Germany, was the first to make use of improved vacuum technology to create a series of astonishingly beautiful evacuated glass vessels into which he sealed metal electrodes. Geissler's **vacuum tubes** emitted brilliant and colourful **fluorescent light** when energised by a high voltage which aroused the interest of both scientists and artists of his day.

1854 English mathematician George **Boole** published "An Investigation of the Laws of Thought, on Which Are Founded the Mathematical Theories of Logic and Probabilities" in which he expressed logical statements in mathematical form. Now known as **Boolean Logic** it also used a **binary** approach to represent whether statements were true or false. It made little impact at the time until twelve years latter it was picked up and developed by American logician Charles Sanders **Pierce**. However it remained in obscurity until it's value was recognised by Claude **Shannon** in 1937 and used to make improvements to Vannevar **Bush**'s analogue computer the differential analyser. Overnight it became the basic **information processing** concept used in all modern computers.

Boole's wife, Mary Everest, niece of Sir George **Everest** after whom the mountain was named, was not blessed with the same logical mind as her husband. in 1864 at the age of 49 Boole caught a serious cold after walking two miles in the rain and giving a lecture still dressed in his wet clothes. His wife believed that a remedy should resemble the cause. She put him to bed and threw buckets of water over the bed since his illness had been caused by getting wet. Boole died of pneumonia.

1855 British chemist and inventor Alexander **Parkes** produced the first synthetic (man made) **plastic**. By dissolving cellulose nitrate in alcohol and camphor containing ether, he produced a hard solid which could be molded when heated, which he called Parkesine (later known as **celluloid**). Unfortunately, Parkes could find no market for the material. In the 1860's, John Wesley **Hyatt**, an American chemist, rediscovered celluloid and marketed it successfully as a replacement for ivory. Thus was born the plastics industry which brought new opportunities to the electrical industry for both insulation and packaging.

1856 As an extension to his "dynamical theory of heat" published in 1851, **Kelvin** submitted a paper to the Royal Society outlining the "**dynamical theory of electricity and magnetism**" treating electricity as a fluid. It was these ideas which led **Maxwell** to develop his theory of **electromagnetic radiation** published in 1873.

In the same year Kelvin invented the **strain gauge** based on his discovery that the resistance of a wire increases with increasing strain.

1857 Following his discovery the previous year that the resistance of a conductor increases with increasing strain **Kelvin** also discovered that the resistance also changes when the conductor is subjected to an external magnetic field, a phenomenon known as magnetoresistance. In bulk ferromagnetic conductors, the main contributor to the magnetoresistance is the anisotropic magnetoresistance **(AMR)**. It is now known that this is due to electron spin-orbit interaction which leads to a different electrical resistivity for a current direction parallel or perpendicular to the direction of magnetisation. When a magnetic field is applied, randomly oriented magnetic domains tend to align their magnetisation along the direction of the field, giving rise to a resistance change of the order of a few percent. The the AMR effect has been used for making magnetic sensors and read-out heads for magnetic disks. See also GMR

1857 **Wheatstone** introduced the first application of **punched paper tapes** (Ticker tapes) as a medium for the preparation, storage, and transmission of data (another one of **Bain**'s ideas) which was rapidly adopted in the USA to speed up the transmission of Morse code.

1858 The laying of the first **Transatlantic Telegraph Cable** from two wooden warships, one of the greatest engineering feats of the nineteenth century, was completed. Financed by American entrepreneur **Cyrus Field,** it was designed and supervised by arrogant and incompetent amateur electrician Dr Edward Orange Wildman **Whitehouse**, a former surgeon from Brighton. Unfortunately the cable failed after less than a month in use, almost before the celebrations were complete, having transmitted only 732 messages. The signal pulses were generated from **Daniell cells** whose voltage was augmented using induction coils. In an attempt to solve the problem of weak signal levels Whitehouse, advised by **Morse** it is claimed, increased the battery voltage from 600 Volts to 2000 Volts with disastrous results causing the breakdown of the cable's insulation. **Kelvin**, a consultant on the project, had advocated solving the weak signal problem by using more sensitive receiving equipment. He had the same year patented a **mirror galvanometer** (originally devised by **Poggendorff** in 1826) which enabled the detection of very weak signals for this purpose which arch rival Whitehouse was reluctant to use, preferring his own detectors. Kelvin's work on this high profile project and his design and management of the subsequent successful cable laid in 1866 enhanced both his reputation and his bank balance as well as his already considerable ego.

It was not until 1956, almost a hundred years later, that the Atlantic was spanned by the first **telephone cable TAT 1**.

1858 German physicist Julius **Plücker** at Bonn University, looking for a way to observe "pure electricity" separate from the conductor carrying it, discovered **cathode rays**. Aware of **Hauksbee**'s glow discharge demonstrations in 1705, he commissioned local glassblower Heinrich **Geissler** to construct an evacuated tube with a metal plate or electrode at each end. Plücker and his assistant Johann **Hittorf** evacuated the tubes using Geissler's "mercury air pump", which produced a much greater vacuum than Hauksbee had been able to achieve. They created an electric discharge between the electrodes and observed what happened in the intervening empty space. At first, with partial vacuum, the tube was filled with an eerie glow just as Hauksbee had found but as the vacuum was increased the glow disappeared and a different greenish glow appeared on the glass near one of the electrodes. Hittorf showed that the glow was due to invisible rays which he called **glow rays** (now called cathode rays) which were emanating from the other electrode. He noticed that they cast shadows when objects were placed in their way indicating that they travelled in straight lines and that they were deflected by magnets indicating that they were electrically charged.

On further investigation Plücker filled the tube with different rarified gases to observe how they conducted electricity and discovered that each gas glowed with a bright characteristic colour like modern day **fluorescent lights**, years before their time. Although this amazing nineteenth century invention was picked up by local shopkeepers to entertain their customers it was never commercialised and seems to have been forgotten until it was rediscovered by **Claude** in the twentieth century.

1858 Scottish linguist and chemist Archibald Scott **Couper** and German chemist Friedrich August **Kekule** von Stradonitz of Czech decent simultaneously and independently recognized that carbon atoms can link to each other to form chains giving birth to the study of **organic chemistry**. Prior to this thinking, it was believed that molecules could only have one central atom. Couper's publication was delayed for three weeks by his reviewer Charles Adolphe **Wurtz** and all credit for the discovery went to Kekule. Couper was devastated and never published another paper.

1858 The **electric burglar** alarm, invented five years earlier by Augustus Russell **Pope**, was first commercialised by American inventor Edwin **Holmes** who is usually credited with its invention. Holmes' workshop was later used by Bell in the development of the telephone and he was the first person to have a home telephone. Holmes' Burglar Alarm business was eventually bought by the American Telephone and Telegraph Company in 1905.

1858 Italian chemist Stanislao **Cannizzaro**, using **Avogadro**'s theories, resolved the confusion between atoms and molecules of the compounds of the same atoms allowing a unified scale for relative **atomic mass** of the elements to be developed.

1859 Scottish engineer and polymath William John Macquorn **Rankine** published his *"Manual of the Steam Engine and Other Prime Movers"* in which he provided a systematic treatment of the theory of steam engines. Building on **Carnot's theory** on the efficiency of heat engines which was based on the thermodynamic cycle of a single gaseous phase reversible process, he recognised that the relationship does not apply if a phase change is encountered, because the heat added or removed during a phase change does not change the temperature of the working fluid. He therfore developed a more general theory of heat cycles for vapour based, closed systems in which the working fluid was alternately vapourised and condensed. Now known as the **Rankine Cycle**, it describes the steam cycle used in modern day electricity generating plants.

1860 The **Lead Acid** battery, the first practical **rechargeable storage battery** was demonstrated by Raymond Gaston **Planté**. It used **spiral wound electrodes** of Lead and Lead Oxide immersed in Sulphuric Acid and despite delivering remarkably high currents it remained a laboratory curiosity for two decades until the manufacturability and performance were improved by **Fauré**. The reversible battery cell chemistry had been observed 60 years earlier by **Gautherot** using copper electrodes but he failed to realise the potential of his discovery. (Sorry!) After over 145 years of development, patents are still being awarded for improvements to this simple device. Currently the value of Lead Acid batteries sold every year in the world is over $30 Billion and still growing.

1860 Concerned with the security of coal supplies, French mathematician Auguste **Mouchout** started work on the design of a **solar powered motor**, the first practical application of **solar energy**. The following year he was granted a patent for his design which used sunlight to boil water in a **solar boiler** to raise steam to drive a conventional motor. By 1865 his efficiency improvements included **solar collectors or reflectors** to catch and focus more of the sun's energy and also a **tracking device** to maintain the optimum orientation towards the sun.

1860 **Maxwell** showed that **white light** can be generated by mixing only three colours not the full spectrum as indicated by **Newton**.

The following year he published "**On the theory of primary colours**" in which he explained that *any* colour, not just white light, can be generated with a mixture of *any* three primary colours. He chose red, green and blue and produced the world's first **colour photograph** at a demonstration of colour photography to the Royal Institution in London in 1861. The subject was a tartan ribbon. Three separate monochrome images were made by exposing the ribbon through red green and blue filters respectively to make three lantern slides. A colour image of the ribbon was then created by projecting the three images from the slides simultaneously on to a screen through three separate lanterns, each equipped with the same filter used to make its image.

Maxwell also developed the **colour triangle**, a practical tool for generating any desired colour. The vertices of the triangle represent the primary colours and the proportions of each primary colour required to generate the desired colour are determined by the distance of the desired colour from each vertex.

Maxwell's work could be considered to be the basis for modern **colorimetry**. **Colour television** and HTML, the language used to generate the colours in Internet browsers, work on the principle of combining red, green and blue primary colours to produce the full spectrum of colours as proposed by Maxwell.

1861 German schoolmaster Johann Philipp **Reis** made the first public presentation of a working **telephone** to Frankfurt's Physics Association (Der Physikalische Verein) and published "Telephony Using Galvanic Current". His transmitter and receiver used a cork, a knitting needle, a sausage skin, and a piece of platinum. Initially fifty units were made but their performance was erratic. Unfortunately Reis suffered from tuberculosis and did not have the time nor the energy to perfect his invention which he called the **"Telephon"**, nor did he find the time to patent it. He died at the age of forty.

1861 Italian immigrant to the USA, fugitive from persecution as a supporter of the Italian unification movement, Antonio Santi Giuseppe **Meucci**, after constructing numerous devices which enabled the transmission of sound, demonstrated a working telephone system in New York. It was based on a system he had devised for communicating between his bedridden wife's room and his workshop in the basement. He called it the **Telettrofono** and it was reported in the local Italian language newspaper *"L'Eco d'Italia"* at the time.

Meucci was perpetually short of cash. He was a prolific inventor but was unsuccessful in commercialising his ideas and this consumed most of his income. Nevertheless he also provided financial support to the leader of the Italian unification movement Giuseppe **Garibaldi** during his exile in the United States.

Meucci continued to devise improvements to his telephone system, including **inductive loading** (in 1870) to enable longer distance calls. Unfortunately, in 1871 when he was incapacitated with serious burns from an explosion aboard the steamship Westfield on which he was travelling, his wife sold all his early models of telephone devices for $6. Meucci could not afford the $250 needed to patent his system, however in 1871 he did manage to obtain a cheaper official "Caveat" stating his paternity of the invention. After the sale of the old prototypes, in 1874 he handed some new models to Western Union Telegraph for evaluation and these were subsequently seen by Alexander G. **Bell** who had access to the laboratory where they were stored. In 1876 he was surprised to read in the newspapers that Bell was credited as the sole inventor of of this amazing new device. United States Patent No. 174,465, issued to Alexander Graham Bell in 1876, became recognized as the world's "most valuable patent." Meanwhile Meucci died in poverty in 1989 bringing to an end the US Government's fraud proceedings against Bell.

Meucci was finally recognised as the first inventor of the telephone by the United States Congress in its resolution 269 dated June 15, 2002, 113 years after his death.

1863 The British government passes the **Alkali Works Act** setting limits to the emissions of noxious substances, one of the first attempts to recognise and control **environmental pollution**. Alkali compounds were widely used at the time in the production of glass, soap, and textiles and were manufactured using the **Le Blanc Process** whose byproducts included various harmful emissions including hydrochloric acid, nitrous oxides,

sulphur and chlorine gas. As a result, manufacturing plants were ringed by dead and dying vegetation and scorched earth and local residents suffered health problems. The new law was backed by the appointment of **Alkali Inspectors** who monitored pollution levels.
One of the founders of modern **chemical engineering** was George E. **Davis** who started his career as an "Alkali Inspector". He stressed the value of large scale experimentation (the precursor of the modern **pilot plant**), **safety practices**, and a **unit operations** approach for controlling chemical manufacturing processes.

1863 Ányos **Jedlik**, then physics professor at the University of Pest in Hungary, introduced his **multiplying capacitor battery** in which a bank of electrostatic generators was used to simultaneously charge a parallel bank (battery) of capacitors. The charged capacitors were then switched to a series connection so that the voltage appearing on the output terminals was equal to the sum of the voltages on the individual capacitors, enabling very high voltages to be built up. He was awarded a gold medal at the 1873 Vienna World Exhibition for his design.

1864 Maxwell predicts that light, radiant heat, and "other radiations if any" are **electromagnetic** disturbances in the form of **waves** propagated through an electromagnetic field according to electromagnetic laws. It was not until 1873 that Maxwell provided the **theoretical justification** for his predictions.

1864 James **Elkington** the owner of a silver plating works in Birmingham, invented a commercial method for the refining of crude copper by the electrolytic deposition pure copper from a solution of copper salts. He patented the idea the following year and 1869 he founded the first **electrolytic refining** plant using this process, at Pembrey in South Wales.

1865 Clausius introduces the concept of **entropy** (from the Greek "transformation") defined as: "The internal energy of a system that cannot be converted to mechanical work" or "The property that describes the disorder of a system".

1865 The **International Telecommunications Union (ITU)**, the world's oldest international organization, an example of **international cooperation** at its best, was established to develop a framework agreement covering the interconnection of the first national and independent telegraph networks which at the time were built and operated to different and often incompatible standards. Its agreements cover interconnections, signalling and message **protocols**, equipment **standards**, operating instructions, tariffs, accounting and billing rules.
Today every telephone whether it is a new push button phone or an old dial phone, an analogue or digital cordless phone, a mobile phone, a payphone or a proprietary office system phone can be connected to every other telephone in the world. The same network is used to connect fax machines and the telephone message may be analogue or digital. The telephone message may be routed to an office in New York, a remote rural village in China or it can find the called party wherever they might be driving their car in Europe, passing through open overhead wires, underground cables, microwave links, fibre optic links, satellite links, undersea cables or local wireless links on the way. The signalling will be understood, the message will get through and the intermediate organisations carrying the call will get paid for their service.
The telephone network used to be **the biggest machine in the world**. Now with the advent of the Internet it is even bigger with computers as well as telephones connected together over the same network with modems carrying data and broadband terminals passing data, video and a host of new services down the same old wires and it still all works thanks to the ITU working anonymously in the background.

1866 Almost thirty years after **Davenport** had built the first practical electric motor using electromagnets in both the stator and rotor, the same technique was applied to the self energising **dynamo**. A wound rotating **electromagnetic armature**, replacing the weaker permanent magnet of the **magneto**, was invented almost simultaneously by Samuel Alfred **Varley** who's design was patented on 12 December 1866, by Werner **Siemens** who publicised his design on 17 January 1867, and by Charles **Wheatstone** who presented a paper to the Royal Society on 4th February 1867 about the principles involved. The design permitted much more powerful and efficient **DC generators**.
It was later revealed that a patent had been granted in 1854 to Mr. Soren **Hjorth**, a Danish railway engineer and inventor for a similar invention with self excited armature coils. Hjorth's patent is to be found in the British Patent Office Library.
The principle had also been demonstrated by Hungarian priest Ányos **Jedlik** in 1861.

The advent of practical dynamos provided a convenient, low cost, inexhaustible source of electric power overcoming many of the limitations of the battery and marked the beginning of electricity generation by electromechanical means rather than by electrochemistry. Rotary generators paved the way for the widespread use of electricity for both high power industrial applications and for consumer appliances in the home.

1867 The **reversibility** of the dynamo was enunciated by Werner **Siemens** but it was not demonstrated on a practical scale until 1873 by **Gramme** and **Fontaine**.

1868 Invention of the **Leclanché cell** carbon-zinc **wet cell** by the French railway engineer Georges Leclanché. It used a cathode of manganese dioxide mixed with carbon contained in a porous pot and an anode of zinc in the form of a rod suspended in an outer glass container. The electrolyte was a solution of ammonium chloride that bathed the electrodes. The manganese dioxide acts as a **depolariser** absorbing hydrogen gas released at the cathode. The first practical battery product to be commercialised, it was immediately adopted by the telegraph service in Belgium and in the space of two years, twenty thousand of his cells were being used in the telegraph system. Later, it was also Alexander Graham Bell's battery of choice for his telephone demonstrations. Domestically however its use for many years was limited to door bells.
Leclanché's electrochemistry was implemented with a different cell construction by **Gassner** in 1886 to make more convenient **dry cells** which still survive today in the form of zinc-carbon dry cells, the lowest-cost flashlight batteries. **Polaroid**'s PolaPulse disposable batteries used in instant film packs also used Leclanché chemistry although in a plastic sandwich.

1868 **Maxwell** analysed the stability of **Watt's** flyball centrifugal governor. Like **Airy**, he used differential equations of motion to find the characteristic equation of the system and studied the effect of the system parameters on stability and showed that the system is stable if the roots of the characteristic equation have negative real parts. He thus established the theoretical basis of modern **feedback control systems** or **cybernetics**.

1868 French engineer Jean Joseph **Farcot** patented improvements to machine control and in 1873 published a book entitled *Le Servo-Moteur* introducing the notion of **servomechanisms** which allow a small control system to control pieces of far heavier machinery.

1869 Prussian physicist Johann Wilhelm **Hittorf** published his laws governing the **migration of ions**. These were based on the concept of the

transport number, the rate at which particular ions carried the electric current, which he had previously developed. He had noted in 1853 that some ions traveled more rapidly than others. By measuring the changes in the concentration of electrolyzed solutions, he computed from these the transport numbers (relative carrying capacities) of many ions.

1869 German chemist Julius Lother **Meyer** discovered the periodic relationship between the elements by plotting a graph of atomic weight against atomic volume, however its publication was delayed by the reviewer.
Working at the same time, this periodic relationship was also noticed by Russian chemist Dimitri Ivanovich **Mendeleyev.** By arranging cards with the names, atomic weights and some properties of the 65 known elements at that time, into rows and columns he noticed an underlying pattern. His **Periodic Table** of the elements was published before Meyer's and the Periodic Table thus became attributed to Mendeleyev. Since then over 700 versions of the table have been produced.
Gaps in the table led scientists to speculate on the existence of hitherto unknown elements with predicted properties related to their positions in the table. The existence and properties of these elements was duly confirmed once suitable experiments could be devised.

1869 French paper manufacturer Aristide **Berges** built the first **hydroelectric generator** at Lancey near Grenoble. Using sluice gates or penstocks, he directed water from a 200 metre high Alpine waterfall through a waterwheel which drove an electrical machine generating 1.5 kiloWatts of power. He coined the expression **hydroelectric power**. Over the years Berges built bigger machines and 1886-1887 he built the world's first **hydraulic accumulator**.

1870 New Yorker John Wesley **Hyatt** patented the first synthetic plastic, now called **Celluloid,** which was invented by **Parkes** in1855. He first used it as a coating for billiard balls and later for denture plates.

1870 John **Player** developed a process of mass producing strands of glass with a steam jet process to make what was called **mineral wool** for use as an effective insulating material. (Editor's Note - I have not yet been able to verify this first statement which could be an oft repeated internet myth related to the next paragraph. Please email me if you can help. The next statement is true.)

John Player had no connection with John Player cigarettes, a major brand in the 1980's. Nevertheless an unfounded rumour spread in the late 1980's and early 1990's, no doubt encouraged by their competitors, that the filters in John Player cigarettes contained **fibreglass** resulting in major damage to their market share.

1870's Austrian physicist Ludwig Eduard **Boltzmann** published a series of papers developing the theory of **statistical mechanics** with which he explained and predicted how the properties of atoms such as mass, charge, and structure determine the visible properties of matter such as viscosity, thermal conductivity, and diffusion. He showed that the kinetic energy of a molecule of an ideal gas is proportional to its absolute temperature. The ratio is equal to 1.38×10^{-23} Joules per degree Kelvin (J/K) and is called the Boltzmann Constant in his honour.

Boltzmann also derived a theoretical relationships for the **thermodynamic entropy** of a gas. 70 years later **Shannon** used an equivalent relationship to define the **information entropy** in a message.

Tragically ill and depressed, Boltzmann took his own life in 1906.

1871 **Weber** proposed the idea for **atomic structure** that atoms contain positive charges that are surrounded by rotating negative particles and that the application of an electric potential to a conductor causes the negative particles to migrate from one atom to another creating **current flow**.

1871 German scientist **Steiner** revived an apparently dead patient by passing a weak electrical current directly through his heart. The first recorded use of **electric shock treatment** for reviving people after **cardiac arrest**.

1872 **PVC**, **Poly Vinyl Chloride** first created by German chemist Eugen **Baumann**. It was not patented until 1913. In 1926 Waldo **Semon** invented a new way of making PVC into a useful product and he is now generally credited with discovering it.

1872 One of the many "Fathers of Radio" West Virginian dentist Mahlon **Loomis** was granted a patent for "a new and Improved Mode of Telegraphing and of Generating Light, Heat, and Motive Power". Although not a true radio system it was an attempt at making a **wireless telegraphy** system by replacing the batteries with electricity gathered from the atmosphere by means of flying kites attached to long copper wires. It used a Morse key between one kite wire and the ground to send signals and at the remote kite it used a galvanometer between the wire and the ground to detect the signals. It is claimed that signals using this method were transmitted over 14 miles, however it is questionable whether this system ever worked and it was never commercially exploited. Nevertheless the Guinness Book of Records credits Loomis with sending the first signals through the air. It was another sixteen years before **Hertz** demonstrated the existence of **radio waves**.

1872 American telecommunications engineer Joseph Barker **Stearns** of Boston developed the first practical telecommunications **duplexing system**. He accomplished this by using two different types of signals, one for each direction. In one direction he used varying strength signals (e.g. On or Off) which he detected with a common or neutral relay, while in the opposite direction he used varying polarity signals (Plus or Minus) which he detected with a polarised relay. The receivers were designed to respond only to signals of the appropriate type from the remote transmitter and to ignore local transmissions. Stearns' system effectively doubled the capacity of the installed telegraph lines and Western Union rapidly acquired rights to use it.

1872 British electrical engineer Josiah Latimer **Clark** invented the **Clark Standard Cell** which provided a reference voltage of 1.434 volts at 15 °C. The cathode was Mercury, in contact with a paste of Mercurous Sulphate, and the anode was Zinc amalgam in contact with a saturated solution of Zinc Sulphate.

1873 Scottish physicist James Clerk **Maxwell** published his "Treatise on Electricity and Magnetism" in which, using a water analogy, he distilled all electromagnetic theory into a set of four rules now accepted as one of the fundamental laws of nature. Now known as **Maxwell's Equations**, they were one of the most important scientific works of the century, not only explaining all electric, magnetic and radiation phenomena known at the time but also providing the foundations for the two great theoretical advances of the twentieth century, **relativity** and **quantum theory**.
Maxwell's four equations express, respectively:

- How electric charges produce **electric fields** - **Gauss' law**.

- The absence of single magnetic poles.
- How currents produce **magnetic fields** - **Ampere's law** with an additional term called the **displacement current** showing that a changing electric field is equivalent to a current also inducing a magnetic field.
- How changing magnetic fields produce electric fields - **Faraday's law of induction**.

In mathematical vector form these complex relationships can be expressed very simply as:-

$$\nabla\bullet \mathbf{D} = \rho$$

$$\nabla\bullet \mathbf{B} = 0$$

$$\nabla \mathrm{x}\ \mathbf{H} = \mathbf{J} + \delta\mathbf{D}/\delta t$$

$$\nabla \mathrm{x}\ \mathbf{E} = -\ \delta\mathbf{B}/\delta t$$

Where

ρ is the free electric charge density (not including dipoles)

D is the electric displacement field or flux density

B is the magnetic flux density

H is the magnetic field

J is the current density

E is the electric field

$\nabla\bullet$ is the divergence operator

∇x is the curl operator

As some physics teachers are fond of saying:

"The Lord said **Let there be light** and there were Maxwell's equations"

These four equations provided the theoretical justification of his **1864 predictions** of the existence of **radiation** or **electromagnetic (radio) waves**, even though at that time there was still no evidence to demonstrate it.

Maxwell showed that electromagnetic fields hold energy which is in every way equivalent to mechanical energy and that a changing magnetic field will induce a changing electric field which in turn induces a changing magnetic field, and so on, such that an electromagnetic wave is created in which the energy oscillates between the electric and magnetic fields.

He also showed that neither the electric wave nor the magnetic wave can exist alone. They travel together, always at right angles and in phase with eachother.

The velocity of propagation of the electromagnetic wave **v** can also be derived from Maxwell's equations as **v = E/B** the ratio between the electric field strength **E** and magnetic flux density **B** which is also equal to $\mathbf{1/\sqrt{\mu_0\varepsilon_0}}$ where μ_0 and ε_0 are the magnetic permeability and the electric permittivity of a vacuum. From a knowledge of the magnitudes of >μ_0 and ε_0 he determined that the velocity of propagation of the electromagnetic wave is constant and equal to the **speed of light** and that light is an electromagnetic wave.

It is a measure of Maxwell's genius that with four elegant and concise equations he could not only account for the movement of a compass needle next to a current carrying wire but with the same equations he was also able to predict, understand and correctly characterise mathematically such a complex phenomenon as electromagnetic radiation that nobody had yet witnessed or even imagined.
Maxwell was initially encouraged and supported in his theories by **Kelvin**, upon whose earlier work he built, however in his lifetime Kelvin never accepted Maxwell's conclusions believing them too theoretical and not related to reality.
It was 1888 before his predictions were proved right by experiments carried out by Heinrich **Hertz**.
In the twentieth century, while **Einstein's relativity theory** required **Newton's laws** to be modified, **Maxwell's equations** remained absolute.

Maxwell also introduced statistical methods into the study of physics, now accepted as commonplace and made significant contributions to structural analysts, **feedback control theory** (**cybernetics**) and the theory of colour taking the first ever **colour photograph**.

Maxwell was a kind and modest man, universally liked. His ideas were ahead of his time but he made no attempt to promote his work. Despite his monumental achievement, it was Hertz' name rather than Maxwell's that has become associated with radio waves and radio propagation.
Maxwell died of stomach cancer in 1879 at the age of forty eight without seeing the experimental confirmation of his theories.

Quotations about Maxwell:
When Michael **Faraday** was asked what was his greatest ever discovery he replied "James Maxwell"

"The Special Theory of Relativity owes its origins to Maxwell's Equations of the Electromagnetic Field" - **Albert Einstein**.

"Ten thousand years from now, there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics" - **Richard Feynman**

1873 Belgian carpenter and instrument maker Zénobe Théophile **Gramme** in partnership with French engineer and inventor Hippolyte **Fontaine** developed the first reliable **commutators** for **DC machines**. (The commutator is the device which reverses the current in the rotor coil as it passes from the influence of one magnet pole to the next magnet pole of opposite polarity in order to maintain a unidirectional current in the external circuit).

They also demonstrated the reversibility of their dynamo by pumping water at the Vienna International Exhibition using two dynamos connected together, one, the generator, deriving motion from a hydraulic engine, provided electrical power to the receiving dynamo which worked the pump. It is said that they discovered the phenomenon by accident when an idle dynamo was mistakenly connected across another working/running dynamo and began motoring backwards. They did however realise that the importance of their discovery was not just the **reversibility of the dynamo**, but also the possibilities **electrical power transmission**. The fact that electrical power could be generated in one place and used in another.

1873 The first demonstration of **electric traction** in a road vehicle by Robert **Davidson** in Edinburgh using iron/zinc primary cells to drive a truck.

1873 English telegraph engineers, Joseph **May** and Willoughby **Smith**, while working with Selenium, noticed that its conductivity changed under the influence of light thus discovering the **photoconductivity** effect.

1873 Dutch physicist Johannes Diederik **van der Waals** deduced more accurate **gas laws** taking into account the volume of the actual molecules making up the gas and the intermolecular forces between them. The **van der Waals forces**, named after him, assumed that neutral molecules behaved like dipoles with a positive charge on one side and a negative charge on the other because their shape was distorted. The true nature of the forces was later explained in 1930 by Polish-born physicist Fritz **London** using quantum theory.
Van der Waals was awarded a Nobel Prize in 1910 for his work on the equation of state for gases and liquids.

1874 A **thermo-electric battery** based on the **Seebeck effect** powered by a gas heater introduced by M **Clamond** in France. Known as the Clamond pile or thermopile, it consisted of a stack of circular arrays of junctions of iron with a zinc-antimony alloy heated by a gas burner located in the centre of the stack. It generated 8 Volts providing a current of 2 to 3 Amps and supplied both heat and electricity to galvanising baths.

1874 Thomas Alva **Edison** invented the **quadruplex telegraph**, which was capable of sending four Morse coded messages simultaneously on a single channel. He amalgamated and rearranged the duplexer of **Gintl**, and **Farmer** and the diplexer of **Stearns** into a single system permitting two messages to be sent in each direction. As with Gintl's duplexer design, two relays in each terminal were unresponsive to outgoing signals, one of these relays responded to current increases of the incoming signals the while the other responded to current reversals of the received signals. Thus Stearns duplexing method of distinguishing between two signals was modified by Edison to separate the signals going in the same direction (diplexing) rather than in opposite directions (duplexing). This avoided the problem of synchronising the receivers with the transmitters. The quadruplex allowed the telegraph lines to carry four times the traffic and saved the telegraph companies millions of dollars.

Edison had started the development of his quadruplex system in 1873 in cooperation with Western Union using their facilities for his experimental work. He had agreed with William **Orton**, the president of Western Union, a development fee and that the patents for the design would be assigned to Western Union. When the design was complete Edison was given $5000 as part payment and $25,000 later. Orton also authorised a royalty payment to Edison of $233 per year before leaving on a business trip. While he was away, Edison was approached by George Jay **Gould**, railroad baron, Wall Street financier, stock manipulator and head of Atlantic and Pacific Telegraph Company, an arch rival of Western Union. He offered Edison $30,000 cash for the quadruplex patents and a job at Atlantic and Pacific. Edison accepted and wrote to Orton saying their arrangement had been a mistake and he revoked the assignment of patents to Western Union. Edison had sold the patents twice over. There followed years of litigation which only ended with the eventual amalgamation of the two telegraph companies. A portent of Edison's business methods to come. See **Edison** and **Tesla**.

Quadruplex telegraphs were eventually displaced by two new inventions, **Baudot**'s multiplex telegraphy capable of eight or more simultaneous transmissions (see next) and **Murray**'s teleprinter machines which did not use Morse code.

1874 Jean Maurice Émile **Baudot**, an officer of the French Telegraph Service made major improvements in the telegraph system by bringing together the **five unit code** devised by **Gauss** and **Weber**, now called the five bit **Baudot code**, and the **synchronous time division multiplex (TDM)** system, proposed by **Farmer** in 1852, into a practical design for a printing telegraph.

The five bit code was the first truly digital code, each unit having only two logical states, giving 32 possible combinations or characters, the shortest practicable code for the number of characters to be transmitted. Baudot used two special characters to switch between letters and numbers giving effectively 64 combinations, enough to allow for 26 characters for the alphabet and 10 numbers plus other miscellaneous punctuation and synchronisation codes. Input was by 5 keys. Later adaptations by **Murray** in 1903 (and others) used five hole punched tape to input the characters with a sixth row of smaller holes to feed the tape through the reader. The tape had the advantage that it could be punched off line and subsequently transmitted at high speed, but more importantly the tapes enabled the transmission speed to be controlled thus facilitating the multiplexing. Early teletypewriters also used Baudot code which eventually supplanted Morse code as the most commonly used telegraphic alphabet becoming known as the International Telegraph Code No.1.
Although the code is now named after Baudot, the five digit binary code was first proposed by **Francis Bacon** in 1605.

The **Baudot distributor** enabled four messages to be transmitted simultaneously. Multiplexing was achieved by using synchronised motors at either end of the line with brushes which connected each channel sequentially, for a fixed interval, to a single transmission line as the motor rotated. Synchronisation codes were sent down the line to keep the transmitter and receiver in step.
In modern circuits **TDM** is accomplished by interleaving the bit streams from the different channels.

The unit of measurement for data transmission rates of one character per second is named the **Baud**, a shortened form of Baudot, in his honour.

1874 German physicist Karl Ferdinand **Braun** discovered one way conduction in metal sulfide crystals. He later used the **rectifying** properties of the galena crystal, a semiconductor material composed of lead sulfide, to create the **crystal detector** used for detecting radio signals which Braun worked on with **Marconi**. Thus was born the first **semiconductor device**. Now called the **diode,** the **cat's whisker** detector was rediscovered and patented 30 years later by **Pickard** and **Dunwoody**.

1874 Irish physicist George Johnstone **Stoney** expanding on **Faraday's laws of electrolysis** and the notion that an electric charge was associated with the particles deposited on the electrodes during electrolysis, proposed that the minimum unit of charge was that which was found on the hydrogen ion and that it should be a fundamental unit. He named it the "**electrine**". In 1891, he changed the name to "**electron**". He calculated the magnitude of this charge from data obtained from the electrolysis of water and the kinetic theory of gases. The value obtained later became known as a **coulomb**. Stoney was unaware of the nature of the atom and "Stoney's electron" is a unit of charge, not to be confused with **J. J. Thomson**'s sub atomic particle which Thomson called a **corpuscle** but which we now call the electron.

1874 David **Salomons** of Tunbridge Wells, England demonstrated a 1 H.P. three wheeled **electric car** powered by Bunsen cells.

1875 American physicist Henry Augustus **Rowland** was the first to show that moving electric charge is the same thing as an **electric current**.
He built up an electrostatic charge on a rotating gramophone (phonograph) record by rubbing it with woolen cloth. A magnetic compass bought in close to the spinning disk was deflected, the magnitude of the deflection increasing with the speed of the disk. This showed that a magnetic field is not only set up by a current moving through a wire but also by a moving electrostatic field.

1876 On March 10 in Boston, Massachusetts, Alexander Graham **Bell**, a Scottish emigré to the USA, invented the **telephone**. Bell filed his application just hours before his competitor, American inventor Elisha **Gray**, founder of Western Electric, filed notice with the same patent examiner, an outline of a telephone he planned to patent himself. What's more, neither man had actually built a working telephone. Bell in particular did not have a working microphone but he made his telephone operate three weeks later using the microphone described in Gray's Notice of Invention, and methods Bell did not propose in his own patent. Being a "system" using several technologies over which Bell claimed sole rights, it spawned more than 600 law suits mostly focused on whether the concept of **modulating** a DC current supplied by a battery was revolutionary or insubstantial and which of the many rivals had thought of it first. Legitimate claimants included Belgian experimenter Charles **Bourseul** (1854), German schoolmaster Johann Philipp **Reis** (1861) and impoverished Italian US immigrant Antonio **Meucci** (1861) to whom the idea is now officially credited by the American Congress (disregarding the prior work of Reis).
Bell's United States Patent No. 174465 became recognized as the world's most valuable patent.

Similar controversies surround the invention of **radio**, but that's another story.

In an attempt to find an assassin's bullet lodged in the body of US President James Garfield, in 1881Bell hastily devised a crude **metal detector** based on the **induction balance** recently devised in 1879 by David **Hughes**. It worked but it didn't find the bullet, indicating that it was deeper than at first thought. It was later discovered that the detector had been confused by the newly invented metal bed springs under the mattress on which the President lay. (The President died after eighty painful days from complications arising from contamination of, and further damage to his wound by the dozen or more doctors probing his body in search of the bullet).

In later life Bell moved to the relative seclusion of his estate in Nova Scotia where he declared himself to be sick of the telephone which he regarded as a nuisance, referring to it as a "beast". He crusaded tirelessly on behalf of the deaf and worked on a variety of projects including flight and aerofoils. At odds with his genuine concern for the deaf, he was an advocate of eugenics and carried out experiments with sheep. He was convinced that sheep with extra nipples would give birth to more lambs, and built a huge village of sheep pens, spending years counting sheep nipples, before the US State Department announced that extra nipples were not linked with extra lambs.

1877 The telephone industry created the next major leap forward in the demand for batteries.

In **Bell**'s original 1876 system the microphone was a **passive transducer** in which the acoustic power of the human voice provided the energy to create the varying electric currents which represent the sound and also to carry them down the wire to the receiver. In Bell's microphone, or transmitter in telephone parlance, sound waves impinge upon a steel diaphragm causing it to vibrate in sympathy. The diaphragm is arranged adjacent to the pole of a bar electromagnet and acts as an armature. The vibrations of the diaphragm cause very weak electrical impulses to be induced in the coil of the electromagnet. However these feeble signals were quickly attenuated as they passed down the telephone line until they were inaudible, severely limiting the range of the circuit and hence the potential of the telephone system.

During 1877 and 1878 German born American Emil **Berliner**, David **Hughes**, Thomas **Edison**, Bell employee Francis **Blake** and English curate Henry **Hunnings**, were each working independently on designs for improved microphones based on **active transducers** in which the acoustic power controls an external source of power. An active transducer provides an electrical signal with about a thousand times more electrical power than the acoustical power absorbed by the transducer and their designs considerably improved the range of the telephone at the expense of requiring power from a local battery. They all used variants of a **carbon transducer** which depend on the fact that the electrical resistance of some materials varies with the physical pressure exerted on it, various forms of carbon material, such as carbon granules, coke or lamp black being particularly sensitive. In the **carbon microphones** which they developed, during the call the battery current flows constantly in a closed circuit across a capsule of carbon material between two terminals one of which is a flexible diaphragm. The sound pressure variations are transferred to the carbon by the diaphragm thus causing the battery current to vary in response to the sound pressure. Edison's design used lamp black and had the added refinement of an induction coil or step up transformer which superimposed the sound information from the transducer on to a separate higher level DC current flowing through the secondary winding of the coil in the main transmission line so that an amplified signal appeared across the terminals of the secondary coil and the stronger DC current carried it further. A process we now call **modulation**.

Rather than patenting his ideas for the microphone, Hughes, who was already wealthy from his invention in 1855 of the **printing telegraph**, communicated his designs to the Royal Society in the February 1878 and generously gave the carbon microphone to the world. This earned him the wrath of Thomas Edison who laid claim to the invention, accusing Hughes of plagiarism and patent infringement. Two months later Berliner and Edison filed for patents on carbon microphones within two weeks of each other resulting in numerous bitter law suits which were eventually settled out of court. Hunnings patented the idea of using carbon granules which could carry higher currents but his patent was challenged by Edison's lawyers. Being a man of limited means he conceded and sold the rights for £1000 and went on Edison's payroll. Berliner went to work for Bell who bought his design for $50,000 and Edison's design, based on principles described by Hughes but using Hunnings' crushed carbon granules became the basis of the standard telephone transmitter and with a few refinements was used for over a hundred years.

Berliner went on to found Deutsche Grammophon Co. and his trademark image became a painting by English artist Mark **Barraud** of his dog "Nipper" listening to **His Master's Voice** for which Barraud was paid £50 for the painting and a further £50 for the full copyright. Berliner's other notable invention was the **gramophone** using a flat disk instead of the cylinder used by Edison.

1877 English experimenter Williams Grylls **Adams** and his student Richard Evans **Day** discovered that an electrical current could be created in Selenium solely by exposing it to light and produced the first **Solar Cells** naming the currents produced this way **photoelectric**. Although the effect was attributed to the properties of Selenium it was in fact due to the properties of the junction between the Selenium, now known to be a semiconducting material, and the Platinum metal used to create the connection for measuring the current.

Note: Confusingly the currents produced by solar cells, named photoelectric currents by Adams and Day, do not arise from the photoelectric effect in which light causes electrons to be emitted from the surface of the material by the process of **photo-emission**. Solar cells or **photovoltaic cells** are made of **semiconductor** material. The incoming light (photons) moves electrons from the valence band across the band gap to the conduction band and the resulting electron-hole pairs cause an internal electrical field to be set up across the **P-N junction** which separates them. In this way different charges on the two electrodes of the solar cell are created, and this potential difference can be used to drive a current through a wire.

It was not until 1954 that the efficiency of photovoltaic cells was improved enough to generate useful power.

1877, German, Ernst **Siemens** patented the first **loudspeaker** before the advent of electrical music reproduction.

1878 Electric **alternator** invented by **Gramme** and **Fontaine**.

1878 American physical chemist Josiah Willard **Gibbs** developed the theory of **Chemical Thermodynamics** introducing the **free energy concept**. When a chemical reaction occurs, the free energy of the system changes. The free energy is the amount of energy available to do external work, ignoring any changes on pressure or volume associated with the change of state. Thus the change in Gibbs free energy represents the total useful energy released by the chemical action which can be made available for doing work. When the free energy decreases, the entropy always increases, and the reaction is spontaneous. (The value of the free energy lies in the fact that its change is easier to measure than the change in entropy.)

He also developed fundamental equations and relationships to calculate **multiphase equilibrium** and the **phase rule** which specifies the minimum possible number of degrees of freedom, or variables such as temperature, pressure, concentration etc. in a (closed) system at equilibrium which must be specified , in terms of the number of separate phases and the number of chemical constituents in the system, in order to completely describe the state of the system. Gibbs' work laid the foundations for the theoretical representation of the energy transfers involved in chemical reactions. This allowed the performance (energy release) of galvanic cells to be quantified and predicted.

He published his work in the Transactions of the Connecticut Academy of Arts and Sciences, an obscure publication, published by his brother in law, with a very limited, mostly local, circulation. His work on thermodynamics, a major advance in the understanding of chemical reactions, therefore remained unknown until 1883, when Wilhelm **Ostwald** a Russian-German physical chemist discovered it and translated it to German.

In 1881 Gibbs published "Elements of Vector Analysis" which presents what is essentially the modern system of **vector analysis**. It permitted the presentation and analysis of complex relationships between multi-dimensional forces such as Maxwell's field theory to be simplified by the use of Gibbs' vector notation and methods. He also made important contributions to the **electromagnetic theory of light**. His later work on **statistical mechanics** was also important, providing a mathematical framework for **quantum theory**.

For all his major contributions to science, Gibbs was a modest man like Maxwell who shunned fame and fortune, living a quiet and contented, simple life as a bachelor, much admired by his students at Yale where he worked.

1878 French electrician, Alfred **Niaudet**, published "Traité élémentaire de la pile électrique" on electric batteries in which he described over **a hundred different battery types** and combinations of elements, indicating the growth and importance of battery technology.

Niaudet described the various chemical mixes and designs which had been used to address a range of design goals. The polarisation problem was solved by using non polarising chemical mixes which did not produce gases, or by using mixes which included depolarising agents or oxidants, which reduced any hydrogen emissions by combination with oxygen. Other recipes were used to achieve higher cell voltages, higher capacity, lower costs or longer life. Alternative constructions were designed to improve the convenience of use and current carrying capability or to reduce the cell's internal resistance. Later the possibility of electrical recharging became a design aim.

Examples not mentioned elsewhere on this web site are given below.

Non polarising 2 Volt primary cells were mostly based on potassium dichromate and often used two electrolyte **gravity cells** (See below).

Examples were:

- 1840 **Grenet**'s single electrolyte potassium dichromate "Bottle" cell with adjustable carbon and zinc electrodes, favoured by **Edison** for his domestic lighting systems.
- **Voisin** and **Dronier**'s potassium dichromate "Bottle" cell, a variation on the Grenet cell with different electrode controls.
- 1842 **Poggendorff** 2 electrolyte cell, similar to the **Bunsen** cell but with potassium dichromate replacing the nitric acid.
- 1852 John **Fuller**'s patented "gravity cell" which had a zinc cathode whose base was immersed in liquid mercury, in a porous container with a dilute sulphuric acid solution. The anode was carbon, surrounded by orange-red potassium dichromate solution and crystals, again in sulphuric acid. Similar cells were patented by **Leffert**. The following year Fuller improved on Daniell's original design to provide the Daniell cell chemistry as we know it today by replacing the aggressive sulphuric acid electrolyte with the more benign zinc sulphate prolonging the life of the cell. He also used the gravity cell construction and the design became very popular for telegraph applications.
- 1854 Gravity cell proposed by C. F. **Varley**
- **Radiguet** 2 electrolyte cell with electrodes of mercury and zinc and electrolytes of sulphuric acid and potassium dichromate.
- **Guiraud** 2 electrolyte cell, a low cost cell with electrodes of carbon and zinc and electrolytes of brine and potassium dichromate

Potassium dichromate is strongly toxic and these cells consequently fell into disuse.

Gravity cells are two electrolyte cells which depend on a lighter electrolyte, such as zinc sulphate, floating on the top of a heavier electrolyte, such as copper sulphate, like oil and water. Normally, diffusion would soon mix the two liquids destroying the cell's efficacy, but if a current was drawn continuously the natural migration of the ions kept the electrolytes apart. This construction reduced the internal resistance of the battery by eliminating the porous pot from the current path. Gravity cells were used extensively in the telegraph and telephone industry, however the inconvenience of keeping the cells undisturbed to avoid mixing the electrolytes and also above freezing temperatures eventually led to their replacement.

Gravity cells which used zinc electrodes suspended in zinc sulphate or sulphuric acid were also called **Crowfoot Cells** because the shape of the zinc electrode resembled the bird's foot.

Other **non polarising** primary cells such as the **Daniell cell** were two electrolyte cells based on copper sulphate and sulphuric acid electrolytes.

These included designs by the following inventors

- **Smée** whose cell was the fore-runner of this class. It used zinc and copper electrodes and the copper electrode was coated with finely-divided platinum intended to cause the evolved hydrogen to form bubbles and detach themselves. An imperfect solution, but the cell was nevertheless popular in the electroplating industry.
- **Carré** who replaced Daniell's porous pot with a parchment membrane.
- **Callaud**, who in the 1860's, eliminated the porous cup in the Daniell cell perfecting the gravity cell construction.

- **Hill** similar to the Callaud cell.
- **Meidinger** whose design was popular in Germany. It used the Callaud chemistry but with a construction which was much easier to maintain.
- **Verité**
- **Minotto** who developed a gravity cell in 1862, based on Daniell's chemistry, for tropical use. It was used by the Indian PTT.
- **Essick** whose cell was designed to operate at 70°C to achieve higher current outputs.
- **Tyer** who patented a mercurial battery with silver and mercury-covered zinc in dilute sulphuric acid.

These cells all produced only 1 Volt which made them less attractive than the 2 Volt dichromate cells.

Many batteries at that time used elemental mercury for contacts or for preventing local action at the zinc electrodes. Impurities in zinc, such as iron or nickel, effectively created minute short-circuited cells around each grain of impurity which soon ate away the zinc. Pure zinc was far too expensive to be considered at that time, however in 1835 William Sturgeon discovered that the local action in the cheaper impure zinc could be eliminated if the zinc electrodes were amalgamated with liquid mercury.
In 1840 Sturgeon developed a long lasting battery consisting of a cast iron cylinder into which a rolled cylinder of amalgamated zinc was placed. Discs of millboard were used as separators and the electrolyte was dilute sulfuric acid.

Depolarising cells from the same period were usually based on nitric acid with a cell voltage of 1.9 Volts and included:

- 1839 **Grove** cell, the first depolarising cell, it was a two electrolyte cell with nitric and sulphuric acid electrolytes and platinum and zinc electrodes
- 1841 **Bunsen** cell, similar to Grove's cell, it replaced expensive platinum with cheaper carbon
- 1853 **Farmer** cell, similar to Grove's cell with improved design of the porous pot.
- 1854/5 **Callan** cell, the **Maynooth** battery, a two electrolyte cell. Expensive platinum or unreliable carbon cathodes were replaced by cast iron. The outer casing was cast iron, and the zinc anode was immersed in a porous pot in the centre.
- Other variants on this theme were developed by Lansing B. **Swan**, Thomas C. **Avery**, Christian **Schönbein, Archeneau, Hawkins, Niaudet, Tommasi** and **d'Arsonval**.

Although these cells were popular, the acid decomposed rather than polarising the cell giving off toxic nitric dioxide gas which eventually led to their demise.

Other developments included:

- The **de la Rue** silver chloride cell whose constant voltage and small size made it popular for medical and testing applications. The electrodes consisted of a small rod or pencil of zinc and a silver strip or wire coated with silver chloride and sheathed in parchment paper. The electrolyte was ammonium chloride contained in a closed glass phial or beaker to avoid evaporation.
- The **Schanschieff** battery which used zinc and carbon electrodes and an electrolyte of mercury sulphate. It was suitable for portable applications such as reading and mining lamps.

All of the above cells were primary cells, but most were designed for re-use. In general, they used aqueous electrolytes enclosed in stout containers, often made of glass. Once the cell was discharged the spent chemicals could be replaced or replenished: - a form of **mechanical recharging**. High volume users such as the telegraph and telephone companies pioneered **recycling**, working with their battery suppliers to reprocess and recover expensive elements from the used electrolytes. (In 1886 Western Union recovered 3000 pounds of copper in this way.)

A further impetus was given to the search for alternative chemistries after 1860 when Gaston **Planté** demonstrated the feasibility of rechargeable cells with his Lead Acid battery.
All of the above primary cells were eventually superceded for PTT use by versions of Planté's rechargeable battery or by mains power.
For portable power, the **Leclanché cell** was one of the few surviving primary cells from this period.

1878 In a letter sent to the publication "Mechanic and World Science" Irish experimenter Denis D. **Redmond** described a 10 by 10 array of Selenium **photocells** each connected to a corresponding array of platinum wires which would glow when light impinged on the photocells. The system was the first to provide electric transmission of moving images, albeit silhouettes, only one year after the discovery of the **photovoltaic effect** and one year before **Edison** patented his light bulb. The system had no image scanning (later provided by **Nipkow**) so it required 100 channels to transmit the image. Nevertheless it was the forerunner of the modern **television** system.

The same year Portuguese professor Adriano **de Paiva** published "La téléscopie électrique basée sur l'emploi du sélénium" in a Portuguese publication "Commercio Portuguez", curiously written mostly in French with some Portuguese. It described a similar system to Redmond's which he called an **electric telescope** anticipating a different application from what eventually transpired.
It was another five years before practical photovoltaic cells were invented by **Fritts**.

1879 American physicist Edwin Herbert **Hall** discovers that when a solid material carrying an electric current is placed in a magnetic field perpendicular to the current, a transverse electric field is created in the current carrier. Known as the **Hall Effect** in his honour. The voltage drop across the conductor at right angles to the current is called the **Hall Voltage** and is proportional to the external magnetic field. Now used in sensors for measuring **magnetic field strength**.

1879 The invention which did more than any other to promote the use of electricity in the home, the **electric light bulb** was patented by Thomas Alva **Edison**. In the early years however the only source of domestic electrical energy generally available was the battery and so all the development took place using DC/battery power.

History is written by the winners and a certain mythology has built up around Edison's inventive genius. The light bulb itself is synonymous with bright ideas but also with Thomas Edison himself. Forgotten however is English experimenter William **de la Rue**'s 1920 **incandescent lamp** using a platinum filament in a partially evacuated glass tube. Forgotten also are all the previous patents for electric lights similar to Edison's using carbon filaments in evacuated bulbs or bulbs filled with inert gas. These included American John W **Starr** from Cincinnati who was granted a UK patent in 1845 for a carbon filament incandescent lamp which he successfully demonstrated to Michael Faraday. Unfortunately Starr was found dead in bed the day after the demonstration at the age of 25, it is said, of "excitement and overwork of the brain" and nothing further became of his invention. Forgotten too are the similar inventions of Alexander **Lodygin** in Russia (1872), Henry **Woodward** and Matthew **Evans** in Canada (1874) and

Joseph **Swan** in the England who demonstrated an almost identical lamp to the Newcastle Literary and Philosophical Society eight months before Edison's "breakthrough". Edison actually sued Swan for patent infringement and the matter was finally settled out of court when the rivals formed the Edison and Swan United Electric Company.

Considering that Edison's name is almost synonymous with the invention of the light bulb it is perhaps surprising to note that in 1883 the US Patent Office ruled that a prior invention patented in 1878 by William **Sawyer** and Albon **Man** took precedence.

See also **Tesla** (1887)

Despite the unfortunate ending to their previous relationship, in 1877 Edison was hired once more by William **Orton** the head of Western Union to try to break Bell's patents on the telephone. Orton is quoted as saying that "Edison had a vacuum where his conscience ought to be". The battlefield was to be the **telephone transmitter** where Bell's design was inadequate but several others were already working on this. Edison provided an innovative design but it also used ideas developed by others and Edison's rights to these were only settled after litigation. He was paid over $100,000 for his solution by Western Union and this gave him the funding and the independence he needed to develop his creative talent. (Bell's lawyers later successfully overturned Orton's main patent challenges to Bell's system although Edison's patents on the carbon microphone were upheld.)

Edison made his first patent application in 1868 when he was 21 years old and over his lifetime he was granted **1,093 U.S. patents** including 106 in 1882. In addition he also filed an estimated 500-600 unsuccessful or abandoned applications. This amounts to two successful patents per week during his most productive period and a patent application on average every eight working days over his long working lifetime of sixty years. Considering that three of these inventions, the light bulb, the phonograph and the movie projector for which he is famous each took several years of development, and at the same time he had a large company to run, you have ask your self how much Edison himself contributed to the patents which bear his name.

Canadian author Peter McArthur is quoted as saying in 1901 "**Every successful enterprise requires three men: a dreamer, a businessman and a son-of-a-bitch**". The giants of the industry seem to embody all three of these characteristics at the same time.

The story of the light bulb is a re-run of the telegraphy and telephony stories, intrigues destined to be repeated with radio, computers, the internet and each new technology advance.

1879 Repeating the 1858 experiment of **Plücker** and **Hittorf** Sir William **Crookes** used a **Geissler** vacuum tube with an anode in the shape of a cross noticed that the cross cast a shadow on a zinc sulfide fluorescent coating on the end of the tube. He hypothesized that there must have been rays coming from the cathode which caused the zinc sulfide to fluoresce and the cross to create a shadow. He called these rays **cathode rays**. Crookes tubes were used by **Röntgen** in 1895 to demonstrate X-rays and by **J. J. Thomson** in 1897 in his discovery of the electron.

Crookes also invented the **radiometer** which detects the presence of radiation. It consists of an evacuated glass bulb in which lightweight metal vanes are mounted on a low friction spindle. Each vane is polished on one side, and blackened on the other. In sunlight , or exposed to a source of infrared radiation (even the heat of a hand nearby can be enough), the vanes turn with no apparent motive power.

Crookes was a believer in the occult and in the 1870's claimed to have verified the authenticity of psychic phenomena. He was knighted by Queen Victoria who, it is rumoured, had similar interests.

1879 Siemens Halske demonstrate an **electric railway** at an exhibition in Berlin. Power was provided from a separate generator which supplied the train via a third rail. A similar system was built in 1883 to run a commercial service along Brighton promenade in the UK by the son of a German clockmaker, Magnus **Volk**, an electrical engineer who had already completed the electric lighting of Brighton Pavilion. It was the world's first **publicly operated electric railway** when it opened and with some modifications his trains are still carrying passengers along the promenade today.

1879 Austrian physicist Josef **Stefan** formulated a law which states that the radiant energy of a blackbody is proportional to the fourth power of its temperature.

1879 After five years working as music professor, Welsh born American David Edward **Hughes** resigned in 1855 to patent a **printing telegraph** which became very successful in the USA and most of Europe, except Great Britain, bringing him international honours. In 1879 he invented the **induction balance**, the basis of the **metal detector**. It consists of two coils, one transmitting a low frequency signal and one connected to a receiver (detector) arranged in such a way that the receiver coil is close to, but shielded from, the transmitter coil so that in free space it does not pick up (detect) any signals from the transmitter. When the coils are brought near to a metal object, small perturbations in the magnetic field upset the balance between the coils causing a current to flow in the receiving coil thus indicating the presence of the metallic object.

The same year while working on his induction balance he noticed a clicking in a separate home made telephone ear-piece. He diagnosed this to be caused by a loose wire in his induction balance since the clicking stopped when the wire was firmly connected. He deduced that invisible waves, which he called **aerial transmissions** and which would today be called **radio waves**, were being emitted from a spark gap which occurred when the wire in the transmitting coil of the induction balance became disconnected and that the ear piece was picking them up. Investigating further he devised a clockwork device for opening and closing the spark gap and was able to pick up signals from the spark gap with his telephone receiver over ever greater distances, up to 500 yards, walking up and down Great Portland Street in London. Effectively he made the world's first **mobile phone** call. In 1880 Hughes demonstrated the phenomenon to the Royal Society in London but the president, mathematician William **Spottiswoode** was not impressed. According to George Gabriel **Stokes**, Irish mathematician and physicist specialising in hydraulics and optics, who witnessed the demonstration, the phenomenon was explained by induction not radio waves. Discouraged, Hughes passed on to other interests and did not pursue his discovery. Eight years later Hertz was credited with the discovery of radio waves.

1880 the brothers Pierre **Curie** and Jacques Curie predicted and demonstrated **piezoelectricity.**

1880 Emile Alphonse **Fauré** in France patented **pasted plates** for manufacturing **lead-acid** batteries. The lead plates were coated with a paste of lead dioxide and sulphuric acid which greatly increased the capacity of the cells and reduced the **formation** time. This was a significant breakthrough which led directly to the industrial manufacture of lead-acid batteries.

1880 Herman **Hammesfahr**, a German immigrant to the USA, was awarded a patent for a durable and flame retardant fibreglass **cloth** with the diameter and texture of silk fibres. He showed a glass dress at the 1893 Chicago World Fair. (Also attributed to American glass manufacturer Edward Drummond **Libbey** founder of Owens-Illinois).

1881 Improvements to the **Leclanché cell**, to avoid leakage, by encapsulating both the negative electrode and porous pot into a sealed zinc cup were patented by J.A. **Thiebaut**.

1881 The first **electric torch** or **flashlight** patented by English inventors Ebenezer **Burr** and William Thomas **Scott**. The original lamps were designed as portable table lamps and powered by a wet cell battery in a waterproof box. At the time the first power station had not yet been commissioned and there were no households wired up for mains electricity. More convenient portable versions of the torch using the recently invented dry cells were introduced starting in 1883. They quickly became popular for bicycle and miners lamps.

1881 Lead acid rechargeable batteries were first used to power an **electric car** by M. G. **Touvé** in France.

1881 The first **International Electric Congress** or **International Conference of Electricians** convened in Paris to define the international terms for the electrical units of electromotive force (**Volt**), resistance (**Ohm**), current (**Ampère**) The Congress also specified the manner and conditions in which the units were to be measured. Up to this time there had been at least twelve different units of electromotive force, ten different units of current, and fifteen different units of resistance.

The standard Ohm was defined by the resistance of a specified column of mercury, the standard Ampère by the current which deposits metallic silver at a specified rate from a silver nitrate solution and the standard Volt was defined by the EMF produced by an electrical circuit passing through an electrical field at a specified rate. However since most laboratories were not equipped to generate a standard Volt in the specified manner, and in any case they used batteries to provide their source of electric potential, a new voltage standard was devised, based on the EMF produced by a standard Clark cell and this was adopted at the fourth International Electric Congress in Chicago in 1893. Unfortunately with the three standards each based on independent measured quantities, Volts did not always equal Amps multiplied by Ohms and the voltage standard had to be changed once more. The 1908 International Congress in London consequently changed the Volt to a derived unit based on the standard Ampère and standard Ohm.

1881 American engineer Frederick Winslow **Taylor** working at the Midvale Steel company introduced **Time and Motion Studies** or **Work Study and Method Studies** to streamline manufacturing and eliminate unnecessary work. They enabled major efficiency savings to be made and became the foundation of **Scientific Management**.

1881 Patent granted to William Wiley **Smith** for the **induction telegraph** used to communicate with moving trains. Soon afterwards improved versions were invented independently by Lucius J. **Phelps** (1884), **Edison** (1885) and black American Granville T, **Woods** (1887). The system consisted of a track-side wire or rail which could pick up signals from an induction coil mounted on the train, essentially acting as the primary and secondary windings of a transformer. The forerunner of the **mobile phone**.

Similar systems, based on the same principle, were also used for fixed **wireless communications** before the discovery of radio (Hertzian) waves.

1882 French physicist and physician Jacques Arsène **d'Arsonval** invented the **moving coil galvanometer**. It had shaped pole pieces which enabled it to have a linear scale and became the basis of all modern electromechanical analogue panel meters.

1882 Nikola **Tesla**, working in Budapest, identified the **rotating magnetic field** principle and the following year used it to design a two-phase **induction motor**.

1882 French chemists Felix de Lalande and Georges Chaperon introduce the first battery to use **alkaline electrolyte**, the **Lalande-Chaperon cell**, the predecessor of the **Nickel-Cadmium cell**. Using electrodes of Zinc and Copper Oxide with a Potassium Hydroxide electrolyte, it was **rechargeable** and produced a voltage of 0.85 Volts.
Up to that point, all batteries had used acidic electrolytes. They chose to investigate alkaline rather than acidic electrolytes because electrodes of most metals and their compounds are attacked by the acid. Lead is one of the few metals resisting the acids but it is very heavy and a weight savings would be secured by using almost any other metal.

1882 English amateur scientist James **Wimshurst** invented the **Wimshurst Electrostatic Generator**, the first machine capable of generating high voltage static electricity that was unaffected by atmospheric humidity. Static electrical charges of opposite polarity built up on its two fourteen and a half inch (38 cm) contra-rotating discs sufficient to draw a four and a half inch (12 cm) spark. Since the breakdown voltage for air is 30,000 Volts per centimetre, this small table top machine was capable of generating over 300,000 Volts. As a reliable source of **high voltage electricity**, it not only provided a practical power source for X-ray machines, but it was a boon to Victorian experimenters enabling them to carry out serious scientific investigations or to carry out dubious experiments in electrotherapy. Wimshurst's basic design is still used in electrical laboratories today.

1882 Ayrton and **Perry** in England build an **electric tricycle** with a range of 10 to 25 miles powered by a lead acid battery and sporting **electric lights** for the first time. (Four years before the first Internal Combustion Engine car by Karl **Benz**)

1882 In a display of optimism the first small domestic electrical appliances begin to appear, three months before power was available from the first electricity generating station. The **electric fan**, a two bladed desk fan was invented by Schuyler Skaats **Wheeler** manufactured by Crocker and Curtis electric motor company and the **electric safety iron** was invented by New Yorker Henry W. **Seely**.

1882 The world's first **central electricity generating plants** or **power stations** were completed by the Edison Electric Lighting Company. The first to come on stream in April was Holborn Viaduct in London powering 2000 electric lamps. The second, in September, was on on Pearl Street in New York City's financial district, supplying 85 customers. Reciprocating Porter and Allen steam engines provided the motive power (about 900 horsepower) to 27 ton **direct-current (DC) dynamos** which produced 100 Kilowatts of power at 110 Volts. The overall energy efficiency is estimated at 6%.

1882 Young American engineer William Joseph **Hammer** testing light bulbs for **Edison** noted a faint blue glow around the one side of the filament in an evacuated bulb and a blackening of the wire and the bulb at the other side, a phenomenon which was first called **Hammer's Phantom Shadow**. In an attempt to keep the inside of the electric lamps free of soot he placed a metal plate inside the evacuated bulb and connected a wire to it. He noted the unidirectional or "one-way" current flow from the incandescent filament across the vacuum to the metal plate but he was unable to explain it or realise its significance at the time. It was in fact due to the **thermionic emission** of electrons (not discovered until 1897 by J.J **Thomson**) from the hot electrode of the filament, flowing to the cold electrode of the plate creating in effect a vacuum diode or valve. In 1884 Edison was awarded a patent for a device using this effect to monitor variations in the output from electrical generators. The indicator proved ineffective however Hammer's discovery of **thermionics** was henceforth known as the **Edison effect**. The Edison effect is the basis of all the vacuum tube devices and thus the foundation of the electronics industry in the early 20th century. The first practical vacuum tube diode was patented by **Fleming** in 1904.

1882 English engineer John **Hopkinson** patented the three-wire, **three phase system** for electricity generation and distribution. This system saved over 50 percent of the copper in the conductor.

1883 Hopkinson demonstrated the principle the **synchronous motor**.
Hopkinson died at the age of 49 in a mountaineering accident in Switzerland, together with one of his sons and two of his three daughters.

1883 Edison patents the **fuse**.

1883 Charles Edgar **Fritts** an American inventor built the first practical **PhotoVoltaic module** by coating selenium wafers with an ultra thin, almost transparent layer of gold. The energy conversion efficiency of these early devices was less than 1%. Denounced as a fraud in the USA for "generating power without consuming matter, thus violating the laws of physics" the idea of **solar cells** was taken up and commercialised by Siemens in Germany.

1883 Irish physicist George Francis **Fitzgerald** suggests that Maxwell's theory of electromagnetic waves indicates that **radio waves** can be produced by an oscillating electric current.

1884 Charles **Renard** uses a Zinc/Chlorine **Flow Battery** to power his **air ship** La France with the chlorine being supplied by an on board chemical reactor containing Chromium Trioxide and Hydrochloric Acid.

1884 Swedish chemist Svante August **Arrhenius** working at the University of Uppsala published his PhD thesis on the **Galvanic Conductivity of Electrolytes** explaining the process by which some compounds conduct electricity when in solution. He proposed that when a compound like table salt NaCl (sodium chloride) was dissolved in water, it **dissociated** into positively and negatively charged "**ions**" (Greek for "the ones that move") Na + and Cl- whose motions constituted a current. These ions drift freely through the solution but when positive and negative electrodes are introduced into the electrolyte, as in electrolysis, the ions drift towards the electrode of opposite polarity. He defined **acids** as any substance, which when dissolved in water, tends to increase the amount of H+ hydrogen ions and **bases** as any substance, which when dissolved in water, tends to increase the amount of OH- hydroxide ions. (These definitions do not cover all possibilities which are now known to exist).
His 1884 thesis was treated with disbelief and was given the lowest passing grade at the time, however he was vindicated with the discovery of the electron by J J **Thomson** in 1897 and his disparaged thesis won him the Nobel Prize for chemistry in 1903.

In 1896 Arrhenius was the first to describe the "**Greenhouse Effect**" and its causes.

1884 French chemist Henri Louis **Le Chatelier** discovered the chemical equivalent of **Lenz Law** of electromagnetism. It was published in simpler form 4 years later as: "If the conditions of a system, initially at equilibrium, are changed, the equilibrium will shift in such a direction as to tend to restore the original conditions". The conditions refer to concentration, temperature and pressure. **Le Chatelier's Principle** allows you to predict which way the **equilibrium** will move when you change the reaction conditions, and helps provide ways to increase the yield in a chemical reaction.

1884 German engineering student Paul Gottlieb **Nipkow** patents an electromechanical **image scanning system** the basis for **television raster scanning**. The system was made possible by use of the **photoconductive properties** of the element selenium recently discovered by **Fritts**. Previous attempts at transmitting images such as **Redmond**'s had used one channel, or pair of wires, to transmit each picture element. Nipkow's design needed only one pair of wires for transmitting the image. He used a rotating disk with holes, through which the scene could be observed, arranged circumferentially around the disc in a spiral between the centre and the edge. Light passing through the holes as the disk rotated, impinged on a selenium photocell, generating an electrical signal proportional to the brightness of the scene which could be transmitted down wires to a receiver. As the disk rotated it produced a rectangular scanning pattern or raster which scanned the scene. The number of scanned lines was equal to the number of holes and each rotation of the disk produced a television frame. A similar **Nipkow disc**, synchronised with the transmitter disc, was used in the receiver and the received electrical signal was used to to vary the brightness of a light source illuminating a projection screen. The light passing through the rotating disk formed a raster on the projection screen allowing an image to be built up. Like all television systems, it depended on the principle of "persistence of vision" and rapid scanning was needed to ensure that it worked. This was the first example of transmitting moving images electrically down a wire however it is not clear whether Nipkow actually built a working system. The signals from the selenium were very low and needed amplification for a practical system and it was not until 1907 that **De Forest**'s **audion** made this possible.

1885 German physicist Eugen **Goldstein** using a cathode ray tube with a perforated cathode discovered rays of positively charged particles emerging from holes on the sides of the cathode and moving in the opposite direction of cathode rays. He called these rays **Canal rays**. The particles were later determined by **Wien** to be **protons** with a mass almost 2000 times the mass of an electron.

1885 Italian physicist Galileo **Ferraris** discovered the **rotating magnetic field** that he applied to the first 4 pole **induction motor**. He did not patent his invention but offered it freely to "the service of mankind"

1885 Russian Nikolai **Benardos** and Polish Stanislav **Olszewski** were granted a patent for an **electric arc welder** with a carbon electrode. They are considered the inventors of modern welding apparatus although electric arc welding was first proposed by **Lindsay** fifty years earlier in 1835.

1885 Engineers from the **Ganz** factory in Hungary, Ottó Titusz **Bláthy**, Miksa **Déri** and Károly **Zipernowsky** demonstrated at the National Exhibition in Budapest, a high voltage **alternating current distribution system** using toroidal **transformers** which they also designed. The entire exhibition was illuminated by 1,067 X 100 Volt incandescent lamps supplied by 75 transformers taking their power from a 1,350 Volt 70 Hz distribution system.

In modern day power transformers the windings are usually wound around a laminated iron (Silicon steel) core (either directly or on a former). The Ganz transformers at the time provided a breakthrough in efficiency because of their unique construction which improved the transformer's **magnetic circuit**. The primary and secondary windings were first wound together in the shape of an annular ring and this formed the core of a toroid. The magnetic circuit was made by toroidally winding thousands of turns of iron wire around the copper windings, completely encasing them in magnetic material which almost filled the inner space of the ring.
Bláthy also patented the first **alternating-current kilowatt-hour meter** in 1889.

1885 German mechanical engineer, Karl Friedrich **Benz** designed and built the world's first practical **automobile** to be powered by an internal combustion engine. It was a "three wheeler", powered by a water cooled 958cc, 0.75hp four stroke engine based on Nicolaus **Otto**'s patent with electric ignition and differential gears. He was granted a patent for the gasoline fuelled "motor carriage" the following year and built his first four wheeled car in 1891. His invention marked the start of the slow demise of the battery driven car.

1886 After **Bláthy's** demonstrations of **alternating current power distribution** the previous year, New Yorker, William **Stanley** Jr in the USA patented the "**Induction Coil**", invented by Michael **Faraday** in 1831, what we would now call a **transformer**. This opened the door to the widespread use of AC power for domestic applications. Battery power, once the only source of electricity in the home, now had a serious competitor.

1886 Carl **Gassner** of Mainz patented the carbon-zinc **dry cell** which made batteries the convenient power source they are today. It used the basic **Leclanché** (1868) cell chemistry with zinc as its primary ingredient with the chemicals being encased in a sealed zinc container which acted as the negative electrode. A carbon rod immersed in a manganese dioxide/carbon black mixture served as the positive electrode. Initially the electrolyte was ammonium chloride soaked into the separator which was made of paper, but by adding zinc chloride to the electrolyte the wasteful corrosion of zinc when the cell was idle was reduced - adding considerably to the shelf life. A bitumen seal prevented leakage. Although the technology has been refined by over a century of development, the concepts and chemistry are the same as Gassner's first cells.
Previously most wet primary cells could be recharged mechanically by replacing the spent chemicals. The used electrolyte could then be recycled to recover the the basic constituents. The advent of the dry cell marked the beginning of the single use, throwaway cell since it was no longer easy or possible for the user to replace or replenish the active chemicals.

1886 Patent granted to American chemist Charles Martin **Hall** for the electrolytic process for extracting **aluminium** from its bauxite ore, aluminium oxide or alumina. His discovery was made in a laboratory he set up at home, using home made Bunsen batteries, shortly after finishing his undergraduate studies. The process was discovered simultaneously by French chemist Paul **Heroult** and is now called the **Hall-Heroult process**.
Aluminium is the most abundant metal and the third most abundant element in the earth's crust but, because it is highly chemically reactive, it does not occur in nature as a free metal. Before Hall discovered a practical way of extracting it from its ore, aluminium metal was extremely rare and cost more than gold.
On an industrial scale the process uses enormous amounts of electricity, consequently aluminium extraction plants are normally located close to the sources of cheap hydroelectric power.

Hall went on to found ALCOA, the Aluminium Company of America.

1887 Kelvin patented the electrostatic **voltmeter**.

1887 **Arrhenius** publishes the equation named after him showing the exponential relationship between the **rate at which a chemical action proceeds** and its temperature, the rate doubling with each 10°C rise in temperature.

1887 American inventor **Elihu Thomson** patents the **electric welding** (**resistance welding**) process. The technique used for making battery interconnections.

1887 By 1887 huge strides had been made in the electrical power industry since the invention of the first practical dynamo 20 years earlier.

1887 - **1890** Croatian-born physicist Nikola **Tesla** filed for numerous US patents on **AC distribution systems** and **polyphase induction motors and generators** based on the **rotating field principle** he discovered in 1882. This enabled inexpensive and unlimited electric power to be brought to the home consumer thus sealing the fate of the **DC system** and the use of DC in domestic applications.
Contracted for $50,000 by Thomas **Edison** (a supporter of **DC transmission**) to improve his DC dynamos Tesla worked night and day to deliver the solutions on time a year later to Edison but Edison refused to pay saying he had been a joking about the contract. Tesla resigned in disgust and went to work for George **Westinghouse** promoter of AC distribution and Edison's arch rival. Edison with some success, spent the rest of his life trying to undermine Tesla.

For two years after Tesla left, Edison staged a morbid public relations campaign in the notorious **current wars** to demonstrate that the Westinghouse AC distribution system was dangerous by promoting the AC powered **electric chair** for carrying out the death penalty and calling such executions "Westinghousing". At the same time he arranged public executions of farm animals which he attended personally in the courtyard of his laboratory using AC power, starting with dogs and escalating to calves then horses.
Edison's system itself was responsible for a number of deaths due to mechanical failure or ignorance as the deceptively similar high voltage wires were installed overhead near to the more familiar low voltage telegraph wires.

In 1915 Reuters and the New york Times carried reports that Tesla and Edison were to share the Nobel Prize for physics. Mystery surrounds what happened next, but no such prize was awarded and it is claimed that Edison, whose fame and wealth were secure, turned down the award to deprive Tesla of a much needed $20,000. Others claim Tesla himself turned it down not wanting to be associated with Edison whom he called "a mere inventor". The Nobel Foundation did not deny that Tesla and Edison had been their first choices.

Despite having over 800 patents Tesla died penniless.

1887 British engineer, born in Liverpool, with the distinctly un-British name of Sebastian Pietro Innocenzo Adhemar Ziani de **Ferranti**, (his father was a photographer and his grandfather, Guitarist to the King of Belgians), designed the generation and distribution systems for **Deptford Power Station** (1887-1890), which at that time was the largest in the world. Power was supplied by four single phase 1000 kW, 10,000 Volts, 85 cycle/sec

alternators. Ferranti pioneered the use of **Alternating Current** for the **distribution** of electrical power in Europe authoring 176 patents on the alternator, high-tension cables, insulation, circuit breakers, transformers and turbines.
Ferranti also designed the first flexible high voltage cables for power distribution using wax-impregnated paper for insulation, a technique which was used exclusively until synthetic materials became available.

In the same year Ferranti also patented the **induction furnace** in which materials are heated by eddy currents induced within the material itself, generated by placing the material in the magnetic field of an induction coil.

1887 British physiologist Augustus **Waller** of St. Mary's Medical School in London published the first human **electrocardiogram** - recorded by lab technician Thomas **Goswell**.

1887 Fibreglass invented again by Charles Vernon **Boys** a physics demonstrator at the London's Royal College of Science who produced **glass fibre** strands by using the end of an arrow fired from a miniature crossbow to draw strands of molten glass from a heated vessel.

1887 German physicist Heinrich Rudolf **Hertz** discovered the **photoelectric effect**, that physical materials emit charged particles (electrons) when they absorb radiant energy. During electromagnetic wave experiments he noticed that a spark would jump more readily between two electrically charged spheres when there surfaces were illuminated by the light from the other spark. Light shining on their surfaces seemed to facilitate the escape of electrons.
The photoelectric effect was not explained until 1905 by Albert **Einstein** who used **quantum theory** proposed in 1900 by Max **Planck**.

1888 Hertz was the first to **transmit and receive radio waves**. He demonstrated the existence of **electromagnetic waves**, predicted by **Maxwell** in 1864 and justified theoretically by him in 1873, by transmitting an electrical disturbance between two unconnected spark gaps situated 1.5 metres apart. He set up a wire loop containing spark gap (the transmitter) through which a large spark was deliberately generated. This caused a small spark to jump across another spark gap (the detector) at the ends of a similar wire loop situated near to but not connected to the transmitting loop. The wire loops were effectively the world's first radio transmitting and receiving antennas.
He showed that radio waves travel in straight lines and can be reflected by a metal sheet.
Hertz died of a brain tumour at the age of 36 without ever seeing the practical applications which resulted from his discoveries. The unit of frequency is named the Hertz in his honour.

Like **Hughes** who discovered the phenomenon before him, Hertz failed to see the potential of radio for communications. Hertz told one of his pupils " I don't see any useful purpose for this mysterious, invisible electromagnetic energy".

Hertz' (or should we say "Maxwell's") radio waves now form the basis of all broadcast radio and television, radar, satellite navigation, mobile phones and much of the backbone of the world's communications systems. Maxwell provided the theoretical basis for the technology, Hertz showed it was possible but there were many, many worthy contributors whose inventions were needed to make it happen. Each country had its national champions who invented transmitters, receivers, antennas, tuners, detectors, filters, oscillators, amplifiers, transducers, displays, batteries and other components and a variety of coding, modulation, multiplexing, compression, encryption schemes, communications protocols and software. There were however five players associated with the fundamental developments in radio technology whose contrasting fortunes are worth mentioning briefly here namely: **Marconi**, **Fessenden**, **Armstrong**, **Watson-Watt** and **Dippy**.

The demand for batteries of course benefited from all of these new developments.

1888 German physicist Wilhelm Ludwig Franz **Hallwachs** discovers another example of **photoelectric emission**. (**Becquerel**'s was the first). Following up **Hertz**' experiments on how light affected the intensity of spark discharges, he noticed that the charge on an insulated, negatively charged plate leaked away slowly but when it was illuminated with ultraviolet light the charge leaked away very quickly. On the other hand a positively charged plate was unaffected by the light. This phenomenon, now known as the **Hallwachs effect**, was later explained to be due to the emission of electrons from certain metallic substances when exposed to light. It is the basis of the modern **photocell**. Note that this is different from the **photovoltaic effect** in **solar cells**.

1888 Spanish naval officer Isaac **Peral** built the first **electrically powered submarine**.

Later the same year the French launched **Gymnôte**, a 60 foot submarine designed by Gustave **Zede**. It was driven by a 55 horse power electric motor, originally powered by 564 **Lalande Chaperon** alkaline cells by **Coumelin, Desmazures et Baillache** with a total capacity of 400 Amphours weighing 11 tons and delivering a maximum current of 166 Amps. These batteries were replaced in 1891 by 204 **Laurent-Cely** Lead acid cells, which were in turn replaced in 1897. Although the batteries were rechargeable, they could not be charged at sea.

An electric submarine was also built by Polish inventor Stefan **Drzewiecki** for the Russian Tzar in 1884.

1888 Austrian botanist Friedrich **Reinitzer** investigating the behaviour of cholesterol in plants observed cholesteryl benzoate changing into its **liquid crystal** state, nine years before the invention of the CRT. For nearly a hundred years afterwards liquid crystals remained little more than a chemical curiosity. See **Dreyer** (1950) and **Heilmeyer**(1968)

1889 Elihu **Thomson** invents the motor driven recording **wattmeter**.

1889 Russian engineer Michail Osipovich Dolivo **von Dobrovolski** working for AEG in Germany made the first **squirrel cage induction motor.**

1889 Walther Hermann **Nernst** a German physical chemist applied the principles of **thermodynamics** to the chemical reactions proceeding in a battery. He formulated an equation (now called the **Nernst Equation**) for calculating the cell voltage taking into account the electrode potentials, the temperature and the concentrations of the active chemicals. It applies to the equilibrium position i.e. no current. This is a special case of the more general **Gibbs free energy** relationship and is one of the basic formulas used by cell designers to characterise the performance of the cell. He also showed that in a reversible system the electrical work done is equal to the change in free energy. Also known as the **enthalpy**.
Nernst stated the **Third Law of Thermodynamics** that it is impossible to cool a body to absolute zero, when it would have zero **entropy**, by any finite process. In a closed system undergoing change, entropy is a measure of the amount of energy unavailable for useful work. At absolute zero, when all molecular motion ceases and order is assumed to be complete, entropy is zero.

1889 America's first **alternating current (AC) hydroelectric power** generating station was put into service at **Willamette Falls**, Oregon. Using **Westinghouse** generators it was also America's first **AC transmission system** providing single phase power at 4000 Volts which was transmitted to Portland 14 miles away where it was stepped down to 50 Volts for distribution and used to power the street lights.

1890 Dundee born engineer James Alfred **Ewing** discovers the phenomenon of **hysteresis** which he named after the Greek "hysteros" meaning "later". He observed that, when a permeable material like soft iron is magnetised by being subjected to an external magnetic field, the induced magnetisation tends to lag behind the magnetising force. If a field is applied to an initially unmagnetised sample and is then removed, the sample retains a residual magnetisation becoming a permanent magnet. He speculated that individual molecules act as magnets, resisting changes in magnetising potential and described the characteristic curve of the magnetic induction **B** versus the magnetic field **H** which caused it, calling it a **hysteresis loop** **(diagram)**. Also known as the **BH loop**, it was later shown by **Steinmetz** that the area of the hysteresis loop is proportional to the energy expended in taking the system through a complete magnetisation - demagnetisation cycle. This wasted energy appears as heat and represents a considerable energy loss in alternating-current machines which are subject to cyclic magnetic fields. On the other hand, hysteresis is useful for creating permanent magnets or temporary magnetic memory, once the main method of providing computer Random Access Memory (RAM).

The hysteresis loop is the signature of a magnet. A slender loop indicates a good temporary magnet which has low hysteresis losses and responds readily to a small magnetic field. Temporary magnets (also known as soft magnets) are needed in magnetic circuits subject to cyclic field such as those found in motors, generators, transformers and inductors. A fat hysteresis loop indicates a permanent magnet, or hard magnet, which will remain magnetized after the application and withdrawal of a large magnetic field.

The term "hysteresis" is now used to describe any system in whose response depends not only on its current state, but also upon its past history.

1891 German born, American mathematician and engineer Charles Proteus (Karl August) **Steinmetz** developed an empirical law for determining the magnitude of the losses due to the recently discovered phenomenon of **magnetic hysteresis** which he published in the magazine, "The Electrical Engineer".

The **Hysteresis law** for the loss of energy per magnetization cycle per unit volume "**W**" is given by **Steinmetz's equation** as

$$\mathbf{W=\eta B}_{max}^{\boldsymbol{x}}$$

where $\mathbf{B}_{max}$ is the maximum flux density, η is the hysteresis coefficient or (a constant depending on the molecular structure and content of the material) and $\boldsymbol{x}$ is the Steinmetz exponent between 1.5 and 2.3, typically 1.6

Steinmetz also provided data on the magnetic characteristics of all magnetic materials then in current use.

As a rule of thumb, when the magnetic flux induced by the alternating current doubles, the hysteresis loss triples. The ability to predict the hysteresis losses for different materials and shapes enabled the design of more efficient machines, a process which had previously been trial and error.

In 1893 Steinmetz developed the **phasor method** using **complex or imaginary number notation** for representing the the varying currents and voltages in AC circuits. This simple and practical method revolutionised the analysis of AC circuits.

Called the Wizard of Schenectady where he worked for General Electric, Steinmetz also carried out research on lightning phenomena. He was a prolific inventor with over 200 patents to his name including an electric car, the 1917 Dey electric roadster, for which he designed a compact double-rotor motor which was an integral part of the rear axle avoiding the need for a differential.

Steinmetz was physically handicapped with a deformed left leg, humped back, and diminutive stature, only four foot three inches (1.3M) tall, but he was compensated by a brilliant mind, congenial personality and infectious vitality. Raised in poverty, Steinmetz was a lifelong socialist whose early political activities brought him into conflict with the German authorities resulting in his flight from Germany. Throughout his life he applied his considerable energies to helping others.

1891 Another patent for the **three-phase electric power** generation and transmission system, this one granted to Jonas **Wenström** a Swedish engineer. His patent was disputed for many years by other claimants, including **Hopkinson** who patented the principle in 1882. It was finally confirmed in 1959, sixty eight years after Wenström died.

1891 American electrial engineer Harry **Ward Leonard** introduced the motor **speed control system** which bears his name. For almost a century, until the advent of thyristor controllers, it was the only practical way of providing a variable speed drive system from the fixed frequency mains electricty supply.

1891 Hertz, with his Hungarian student Philipp Eduard Anton von **Lenard**, discovered that **cathode rays** could penetrate a thin aluminium plate. Because gas could not pass through the foil they surmised that the cathode ray was a wave, publishing their results in 1894. In 1897 **J.J. Thomson** showed that cathode rays were streams of particles which he called corpuscles and which we now call electrons.
Lenard was awarded the Nobel Prize for Physics in 1905 for his work on cathode rays. He was a strong proponent of the German "Master Race" and became Adolf Hitler's advisor and Chief of "**Deutsche Physik**" or "Aryan Physics". He claimed that so called "English physics" had stolen their ideas from Germany and denounced Einstein's theory of relativity as a deliberately misleading Jewish fraud perpetrated by "Jewish physics". He was expelled from his post at Heidelberg University by the Allied occupation forces in 1945.

1892 British born American chemist Edward Weston invented and patented the saturated cadmium cell. Known as the **Weston Standard Cell**, it was adopted as the International Standard for electromotive force (EMF) in 1911 and was used as a calibration standard by the US National Bureau of Standards for almost a century. It had the advantages of being less temperature sensitive than the previous standard, the Latimer **Clark Standard Cell** which it replaced and of producing a voltage of 1.0183 Volt, conveniently near to one Volt. Similar to Clark's cell it used a Cadmium anode rather than Zinc.
He had revolutionised the electroplating industry in 1875 by replacing the batteries used to provide the current used in the plating process with dynamos which he designed and made himself and in 1886 he developed a practical precision, direct reading, portable instrument to accurately measure electrical current, a device which became the basis for the moving coil **voltmeter, ammeter and watt meter**.
A prolific inventor Weston held 334 patents.

1892 The **Hayes** patent paved the way for telephone signalling and speech to be powered from a single large **central 24 Volt lead acid batteries** mounted in **central telephone exchanges**, eliminating the need for magnetos and Leclanché cells installed in every subscriber's premises. The system is still in use today.

1892 Eccentric Kentucky melon farmer Nathan B. **Stubblefield** "demonstrated" **wireless telephony** using a **ground battery** or **earth battery** (first proposed by **Bain** in 1841), for transmitting signals through the ground. Extravagant claims were made for the applications of the ground battery, from telephony and broadcasting to power generation, but they were never substantiated and Stubblefield, claiming he was swindled, died of starvation, an impoverished recluse. He is honoured in his hometown of Murray, Kentucky as "**The Real Father of Radio**".

1892 Dutch physicist Hendrik Antoon Lorentz formulates **Lorentz Law**, a fundamental equation in **electrodynamics** which gives the force **F** on a charged particle in an electromagnetic field as the sum of the electrical and magnetic components as follows:

$$\mathbf{F} = q\mathbf{E} + qv \times \mathbf{B}$$

Where q is the charge on the particle, v is its velocity, **E** is the electric field and **B** is the magnetic field.

Lorentz developed a mathematical theory of the electron before their existence was proven for which he received the Nobel Prize in 1902

1893 Two German schoolmasters Johann Phillip Ludwig (Julius) **Elster** and Hans Friedrich **Geitel** discovered the sensitive **photoelectric effect** of alkaline metals such as sodium or potassium in vacuum tube at visible light spectrum. They later design the first practical **photoelectric cell** or **"electric eye"** which provides a voltage output which varies in relation to the intensity of light impinging upon it. They decline to patent their invention. The photoelectric effect is the basis of all electronic image tubes.

1893 Contract to supply hydroelectric generators to harness the power of **Niagara Falls** using **Tesla**'s AC system awarded to **Westinghouse**, signalling the beginning of the end for DC generation and transmission, the end of the **Current Wars** and a triumph for Tesla. Rival **Edison** had lined up influential backers including J. P. Morgan, Lord Rothschild, John Jacob Astor IV, W. K. Vanderbilt and initially **Lord Kelvin**, a proponent of direct current, who headed an international commission to choose the system. After seeing Tesla's AC system which was used to light the 1893 World's Columbian Exposition at Chicago, Kelvin was converted to a be supporter of the AC system.

The system was completed in 1895 with three enormous 5,000 horsepower generators supplying 2,200 Volts for local consumption, stepped up to 11,000 Volts for transmission to Buffalo 22 miles away. The capacity was later increased to 50,000 horsepower with 10 generators and the transmission Voltage increased to 22,000 Volts for longer distance transmission.

1894 British engineer Charles Algernon **Parsons** had produced his first **steam turbine** in 1885 but had failed to generate any commercial interest in it. To publicise his invention, in 1894 he took out a patent on the turbine and commissioned a 100 foot long steel boat, the **Turbinia**, to demonstrate its capability. Initially he did not achieve the desired speed through the water as its propellers, rotating at 18,000 rpm, suffered from the previously unheard of problem of cavitation and churned up the water as bubbles formed behind the blades due to sudden pressure reduction. However by slowing down the turbine and modifying the propellers he was able to achieve a speed of 34.5 knots. Still his target customer the Admiralty were unimpressed. According to Parson's biographer Ken Smith, Parsons dictum was "If you believe in a principle, never damage it with a poor impression. You must go all the way". His opportunity came at the 1897 Spithead Naval Review of 160 of the navy's ships, arranged to show off the might of the Royal Navy to Queen Victoria and invited foreign dignitaries on the sixtieth anniversary of the queen's accession to the throne. The navy's best boats were capable of no more than 30 knots and the Turbinia astonished the gathered crowd by steaming up and down the navy's lines leaving their fastest boats in her wake. The steam turbine's future was assured. Today 86% of the world's electricity is generated using steam turbines.

1895 German physicist Wilhelm Conrad **Röntgen** experimenting with a **Crookes tube** accidentally discovered **X-rays** while investigating the glow from the cathode rays and gave his preliminary report "Uber eine neue Art von Strahlen" to the president of the Wurzburg Physical-Medical Society, accompanied by experimental **radiographs** and by the image of his wife's hand. Within three years, every major medical institution in the world was using X-rays. Röntgen, who won the first Nobel prize in physics in 1901, declined to seek patents or proprietary claims on the use of X-rays. X-ray technology is now widely used in materials science. See **Bragg** (1912)

1895 French physicist Pierre **Curie** discovered that the magnetic coefficients of attraction of **paramagnetic bodies** vary in inverse proportion to the absolute temperature -- **Curie's Law**. He showed that **ferromagnetic materials** exhibit a characteristic temperature, now called the **Curie point** or **Curie temperature**, above which they lose all their magnetic properties. He also showed that there is no temperature effect for **diamagnetism**.

1896 Inspired by **Hertz**, 22 year old Italian Marchese Guglielmo **Marconi**, son of the Irish-born heiress to the Jameson whiskey fortune, was granted his first patent (in England) for **radio telegraphy** using Hertzian waves. This was the first application of radio waves and he was the first to show that radio communications were possible. His system however was the radio equivalent of Morse's telegraph, switching the radio wave on and off in "dots and dashes", and it did not carry voice signals. It was **Fessenden** who first carried voices over the radio waves ten years later. Marconi was a great promoter, he developed transmitters, receivers and antennas and his telegraph systems were soon in use throughout the world, spanning the Atlantic in 1901, and earning him fame and fortune. He was awarded the Nobel prize for physics in 1909.

1896 American engineer William W. **Jacques** developed a **carbon battery** producing electricity directly from coal. 100 cells with carbon electrodes and alkaline electrolyte were placed on top of a coal fired furnace that kept the electrolyte temperature between 400-500 °C and air was injected into the electrolyte to react, he thought, with the carbon electrodes. The output was measured as 16 Amps at 90 Volts. Initially, Jacques claimed an 82 percent efficiency for his battery, but he had failed to account for the heat energy used in the furnace and the energy used to drive an air pump. The real efficiency was a meager 8 percent. Further research demonstrated that the current generated by his apparatus was not obtained through electrochemical action, but rather through **thermoelectric** action.

1896 Antoine Henri **Becquerel** discovered **radioactivity** when Uranium crystals wrapped in paper and left in a drawer with photographic plates created an image of the crystals on the plates. Radioactivity is the spontaneous breakdown of unstable atomic nuclei resulting in the emission of radiation which may be **alpha particles** (Helium nuclei), **beta particles** (electrons), **nucleons** (neutrons or protons), or **gamma rays** (high energy electromagnetic radiation). At the time however the nature of these mysterious rays was not known and it was several years before **Rutherford**

and others were able to identify the content of the radiation.

Radioactivity can come from the decay of naturally occurring **radioisotopes**. Nuclear batteries are designed to make use of the radiated energy of certain radioactive isotopes by converting it into electrical energy.

Becquerel came from a distinguished family of scholars and scientists. His father, Alexandre-Edmond Becquerel, was a Professor of Applied Physics, discovered the photovoltaic effect and had done research on solar radiation and on phosphorescence, while his grandfather, Antoine César Becquerel, had been a Fellow of the Royal Society and invented a non polarising battery and an electrolytic method for extracting metals from their ores.

1896 In the USA, the **flashlight** or **torch** was invented by David **Misell**. The original versions were designed to attach to a tie or scarf and were sold by a Russian immigrant, Conrad **Hubert** in his novelty shop where Misell went to work. Although portable battery powered lamps had been in use in the UK since 1881 where they were patented by Burr and Scott, the first flashlight as we know it today introduced by Hubert in 1898. It was designed by Misell and was powered by a **"D" cell** which, with the light bulb and a rough brass reflector, was contained in a paper tube. Hubert went on to found **Ever Ready** and patents for subsequent flashlights although designed by Misell were awarded to Hubert.

The invention of the tungsten filament lamp by **Coolidge** in 1910 greatly improved the performance of the torch which in turn created a growing market for batteries, popularising the "D" cell format we still use today.

1896 H. J. **Dowsing** patented the **electric starter** which he fitted to a modified Benz motor car purchased from maker Walter **Arnold** who made them under licence as the Arnold Sociable in East Peckham, Kent. Dowsing's starter consisted of a dynamotor, coupled to a flywheel, which acted as a dynamo to charge the battery and as a motor when needed to start the engine, an idea recently rediscovered as the **integrated starter alternator (ISA)**. The first production electric **self-starter** was produced by **Dechamps** in Belgium in 1902.

1897 British physicist Joseph John **(J J) Thomson** working at the Cavendish Laboratory in Cambridge investigating the affect of magnetic fields on cathode rays in a Crookes tube discovered the **electron** and calculated the ratio between its charge and its mass, **the e/m ratio**. He determined that they were identical particles no matter what metal had emitted them and that they were the universal carriers of electricity and a basic constituent of matter. He also calculated the velocity of the electron in the cathode ray to be 1/10 of the speed of light. J.J. Thomson was awarded the Nobel prize in 1906 for his studies on the conduction of electricity through gases and for the discovery of the electron and his pioneering work on the structure of the atom.

At the time there was great rivalry between German researchers who believed cathode rays to be waves and their British counterparts who believed them to be particles. In one of the greatest ironies of modern physics J.J. Thomson was awarded the Nobel Prize for showing that the electron is a particle, while his son, George Paget Thomson later received the Nobel prize for proving that the electron was in fact a wave.

Seven of Thomson's students went on to gain Nobel prizes in their own right.

Thomson died in 1940 and in his lifetime he never drove a car or travelled in an aeroplane. He had a passion for nature and said that if he had to live his life over again he would be a botanist.

Ever since **Faraday** published his work on the magnitude of the weights of the products of **electrolysis** in 1833, experimenters had postulated the idea that electric current was carried by corpuscles or particles but none had been able to isolate or describe such particles. By the late 1890's however, several other investigators working contemporaneously with Thomson had identified the charged particle we now call the electron and calculated the e/m ratio just as Thomson did in April1897. These included Pieter **Zeeman** at the University of Leiden who in 1896 observed the spreading of spectral lines caused by the influence of a magnetic field and concluded that the light waves were produced by the movement of ions. From the experiment he was able to calculate the e/m ratio. At the same time, each working independently with cathode rays, Emil **Weichert** at the University of Köningsburg, Walter **Kaufmann** at the University of Berlin and Philipp **Lenard** an assistant of Heinrich **Hertz** carrying on Hertz' experiments after his death, all published similar results for the value of the e/m ratio early in 1897. It was Thomson however who identified the electron as a sub atomic particle, while the others were hampered by trying to reconcile the evidence of a particle with the notion of the aether.

History is kind to the winners of **Nobel prizes**. Once conferred, the other participants in the race are forgotten.

1897 The first **oscilloscope** using a **cathode ray tube (CRT)** scanning device was invented by the German scientist Karl Ferdinand **Braun**. He made many contributions to radio technology including **antennas** and **detectors**. He was awarded the Nobel prize with **Marconi** in 1909 for this work. During the first World War he was interned by the US government as an enemy alien and died before the war ended.

1897 **Regenerative braking** first used on a car to recharge the battery by M. A. **Darracq** in Paris

1897 German researcher W. **Peukert** discovered that the faster a battery is discharged the lower its available capacity, a phenomenon for which he developed the empirical law $C = I^n T$ known as the **Puekert Equation** where "C" is the theoretical capacity of the battery expressed in amp hours, "I" is the current, "T" is time, and "n" is the Peukert Number, a constant for the given battery. A similar phenomenon occurs when a battery is charged. See also **charging times** for an explanation and a beer analogy.

1898 Danish telephone engineer Valdemar **Poulsen** patented the Telegraphone, the first **magnetic recording and playback apparatus**. It used a magnetised wire as the recording medium.

1898 The **Proton** discovered by German physicist Wilhelm **Wien**. Using an apparatus designed by **Goldstein** which generated **canal rays** of positively charged particles he determined that canal rays were streams of protons with mass equal to the mass of a Hydrogen atom. **Rutherford** later coined the word proton in 1919.

Wien also discovered the inverse relationship between the wavelength of the peak of the emission of a black body and its temperature now called **Wien's Law**. He was awarded the Nobel Prize in 1911 for his work on Black Body Radiation.

1898 British physicist Oliver Joseph **Lodge** patented the principle of **tuned circuits** which he called "syntonic tuning" for generating and selecting particular radio frequencies. This is the basis of selecting a single desired radio station from all those which are transmitting by tuning the receiver to the transmitter. Not only was this more efficient, it was fundamental to the orderly use of the radio spectrum and the establishment of practical radio communications systems which did not interfere with eachother.

1898 Pierre and Marie Sklodowska **Curie** discovered **Radium** named from the Latin "radius" meaning "ray" and **Polonium** which Marie named after her native Poland. With very limited resources, during the course of four years, the Curies refined 8 tonnes of waste pitchblende to produce 1 gram (0.04 ounces)of pure Radium Chloride. (It was not until 1911 that she was able to isolate pure Radium). Radium is over one million times more radioactive than the same mass of Uranium and one gram of Radium releases 4000 kilo joules (1.11 KWh) of energy per year. In 1900 they showed that beta rays and cathode rays are identical. Unaware at the time of the dangers of radiation in 1903 they both began to show signs of radiation sickness. Marie shared the 1903 Nobel Prize for Physics with her husband Pierre and Henri **Becquerel** for the investigation of **radioactivity**, a phenomenon which she named. In 1906 Pierre was unfortunately killed when he was run over by a horse drawn cart. Marie continued their investigations and in 1911 was awarded a second Nobel Prize, this time for Chemistry for her discovery of two new elements. Despite her achievements and her two Nobel prizes, she was rejected by the French Academy of Sciences when seat for a physicist became vacant. During her life she worked tirelessly for humanitarian causes and the use of X-rays and radioactivity in medical research, refusing to patent any of her ideas. She died of leukaemia caused by prolonged exposure to radioactivity. Her laboratory notebooks are still considered too radioactive to handle and photographic films, when placed between the pages, show the images of Madame Curie's radioactive fingerprints when developed. A year after her death, her daughter Irene won the family's third Nobel Prize.

1899 Charles H. **Duell** Commissioner in the **US Office of Patents** announced "Everything that can be invented has been invented"

1899 Working at McGill University in Montreal on **Becquerel's** mysterious rays, New Zealand physicist Ernest **Rutherford**, assisted by English chemist Frederick **Soddy**, discovered two kinds of "rays" emanating from the Uranium, one of which he called the **alpha rays**, could be absorbed by a sheet of writing paper. The other which he called **beta rays** was one hundred times more penetrating but could be stopped by a thin sheet of aluminium. Meanwhile French physicist Paul Ulrich **Villard** found that Radium emitted some far more penetrating **radiation**, which he christened **gamma rays**. These rays could penetrate several feet of concrete.
It was still some time before the properties of all these different rays could be determined.

- By 1900 Becquerel succeeded in deflecting the beta rays with a magnetic field proving that the rays were in fact streams of charged particles. He also measured the e/m ratio of the particles which turned out to be close to that of cathode rays suggesting that the beta rays were in fact streams of electrons.
- It was not until 1903 that Rutherford was able to deflect the alpha rays and it was 1905 before he could measure the e/m ratio. His results showed that the rays were in fact particles with the opposite charge from an electron. He concluded that if the charge on an alpha particle was the same as that on a hydrogen ion, the mass of the alpha was approximately twice that of the hydrogen atom. In 1908, he finally established that the alphas were helium atoms with two electrons missing, carrying charge 2 *e* , and having mass four times that of the hydrogen atom.
- Gamma rays were not deflected by a magnetic field which showed them to be rays and not particles. They were found to be similar to x-rays, but with much shorter wavelength. This was not settled until 1914, when Rutherford observed them to be reflected from crystal surfaces.

1899 First patent on **Nickel Cadmium** **rechargeable cells** using **alkaline chemistry** taken out by Waldemar **Jungner** of Sweden

1899 The world land speed record of 68 mph was set by a Belgian built **electric car**, the "Jamais Contente", designed and driven by Camille **Jénatzy**. The first to exceed 100 kph, his cigar shaped car was powered by two 80 cell Fulmen Lead acid batteries supplying two twelve volt, 25 kilowatt motors, integral with the rear axle, driving the rear wheels directly.
Jénatzy, known as the Red Devil because of his red beard, was a famous racing driver at the time when racing was very dangerous, however his life was ended at his country estate rather than on the race track when, hosting a shooting party, he sneaked into the woods to imitate a roaring bear and was shot by one of his friends.

1899 Young German engineer Ferdinand **Porsche**, working at the Jacob **Lohner** Company, built the first **Hybrid Electric Vehicle (HEV)**, a series hybrid, optimised for simplicity and efficiency. It used a petrol engine rotating at optimum, constant speed to drive a dynamo which charged a bank of batteries which in turn provided power to hub mounted electric motors in the front wheels. 300 Lohner Porsches were produced.

1900 Thomas Alva **Edison** in the USA also patents a rechargeable alkaline cell, the **Nickel Iron (NiFe)** battery. Another one of Edison's **1093 patents**.
Nickel Iron batteries were very robust, designed for powering electric vehicles, but with the rise of the internal combustion engine their main applications became railway traction, fork lift trucks and utilities.

1900 Sales of internal combustion engined cars overtake sales of **electric cars** for the first time.

1900 German physicist **Max Planck** announced the basis of what is now known as **quantum theory**, that the energy emitted by a radiating body could only take on discrete values or **quanta**. Planck's concept of energy quanta conflicted fundamentally with all past classical physics theory and eventually gave birth to the particle theory of light as later explained by Albert Einstein. Although its importance was not recognised at the time, quantum theory created a revolution in physics. Planck was driven to introduce it strictly by the force of his logic; he was, as one historian put it, a reluctant revolutionary.
The energy **E** in a quantum of light, now called a **photon**, or resonator of frequency ν is $h\nu$ where h is a universal constant equal to 6.63 X 10^{-34} Joule seconds (Js), now called **Planck's constant**.
He was awarded a Nobel prize in 1918 for his work on quantum theory.

Planck's personal life was a tragic one. His first wife died early leaving Planck with two sons and twin daughters. The elder son was killed in action in 1916 in the First World War. Both of his daughters died in childbirth. World War II brought further tragedy. Planck's house in Berlin containing his technical papers was completely destroyed by bombs in 1944. Far worse his younger son died while being tortured by the Gestapo after being implicated in the attempt made on Hitler's life in 1944. Planck died in 1947 at the age of 88.

1900 German physicist Paul Karl Ludwig **Drude** developed a model to explain **electrical conduction** based on the kinetic theory of electrons moving through a solid.

1900 Belgian car maker, **Pieper**, introduced a 3½ horsepower "**voiturette**" another variant of the **hybrid electric vehicle (HEV)**. An electric motor/

dynamo was mounted in line with a small petrol engine and acted as a generator during normal driving, recharging the batteries. For hill climbing the motive power was augmented by battery power as the electric motor was switched to supplement the power of the engine.
Later versions used higher capacity batteries (28 Tudor batteries in series) and a 24 horsepower engine connected to a higher power electrical drive via a magnetic clutch. The clutch mechanism allowed energy to be recovered by **regenerative braking** as well as the use of the higher power electric motor to drive the vehicle on its own.

1900 Irish born American John P. **Holland** launched his first submarine the Holland I in 1878. A crude design, carrying a crew of one, it was powered by a petrol engine and ran on compressed air when submerged. Holland was a sympathiser of the Fenian Brotherhood, an Irish revolutionary secret society, forefathers of the IRA, founded in the United States. He designed the Fenian Ram, a three man submarine which was launched in 1881, for attacking British shipping. Finding the Fenians unreliable customers he made several unsuccessful attempts to sell his submarines to the US government, eventually launching his sixth submarine the Holland VI in 1898. It was a **dual propulsion submarine** the which used a 45 h.p. Otto petrol engine for propulsion and battery charging while on the surface and a 110 Volt electric motor powered by 60 Lead Acid cells with a capacity of 1500 ampere hours for propulsion when submerged. This time his demonstration was successful and the submarine was purchased by the US government. It was commissioned in 1900 and renamed the USS Holland, also known as the SS1, becoming the US Navy's first submarine. Although it carried a crew of only five plus an officer, the Holland VI was a major breakthrough in submarine design. For the first time, all the major components were present in one vessel - dual propulsion systems, a fixed longitudinal centre of gravity, separate main and auxiliary ballast systems, a hydrodynamically advanced shape, and a modern weapons system. The configuration and design principles used in the Holland VI remained the model for all submarines for almost 50 years.

1901 Patent granted to **Michaelowski** in Russia for the rechargeable **Nickel Zinc** battery.

1902 The **Mercury Arc Rectifier** invented by American engineer Peter Cooper **Hewitt**. A spin off from developments of the mercury arc lamp it was capable of rectifying high currents and found use in **electric traction** applications which used DC motors.

1902 Twenty years after the introduction of electricity supply in the USA only 3% of the population were served by electricity.

1903 The invention **Electrocardiograph** by Indonesian born Dutchman Willem **Einthoven** was announced after a long gestation period. Building on **Waller**'s work of 1887 (and the contributions of many others following in the footsteps of Galvani) it used a sensitive "string galvanometer" of Einthoven's own design to pick up small electrical currents from the patient's torso and limbs. (**Galvani**'s theories about **Animal electricity** vindicated?)
Einthoven is now credited with the design of the electrocardiograph for which he received the Nobel Prize in 1924.

1903 Following on from their work on **radiation**, **Soddy** and **Rutherford** proposed that the phenomenon of **radioactivity** was due to the **spontaneous atomic disintegration** of unstable heavy elements into new, lighter elements, an idea which, like many new scientific theories, was treated with derision at the time.
Soddy was a chemist and Rutherford a passionate physicist who believed that chemistry was an inferior science to physics. Ironically it was

Rutherford rather than Soddy who was honoured in 1908 with the Nobel Prize for chemistry for the discovery of **radioactive transformation**. Afterwards Rutherford liked to joke that his own transformation into a chemist had been instantaneous. Soddy resented the the fact that his contribution had not been recognised. He was however eventually awarded a Nobel prize in 1921 for his work on isotopes but that did little to mitigate his earlier slight.

1903 British Patent awarded to German Albert Parker **Hanson**, living in London, for **flexible printed wiring circuits** intended for use in telephone exchanges. Based on flat parallel copper conducting strips bonded to paraffin waxed paper. The design used a double layer construction with the copper strips in alternate layers perpendicular to the layer below forming a rectangular grid. Interconnections were crimped through holes in the paper. As well as through hole connections, Hanson's patent also described double-sided and multilayer boards.

1903 The Compagnie Parisienne des Voitures Electriques produced the **Krieger** front wheel drive **hybrid electric vehicle (HEV)** with power steering. A petrol engine supplements the battery pack.

1903 Russian botanist Mikhail Semenovich **Tswett** invented the technique of **chromatography** (Latin "colour writing") which he demonstrated by passing extracts of plant tissue through a chalk column to separate pigments by differential adsorption. It was derided at the time but the principle is now used universally for separating and identifying different chemical compounds from samples.

1903 The **teleprinter** machine (a.k.a. teletypewriter, teletype or TTY) invented by New Zealand sheep farmer Donald **Murray**. It could punch or read five digit **Baudot coded** paper tapes (Murray used his own modified version) and at the same time print out the message on a sheet of paper. It de-skilled the telegraph operator's job, since they no longer needed to know Morse code, and at the same time greatly speeding data communications. The teleprinter remained in widespread use until the 1970's when electronic data processing and computer networking replaced many of its functions.

1904 British physicist John Ambrose **Fleming** invented the first practical **diode** or **rectifier**. Although first used in radio applications it became an important device for deriving direct current from the alternating current **AC** electricity distribution system, revitalising opportunities for **DC** powered devices, and indirectly, batteries. Fleming's invention of the **thermionic valve** (tube) could be said to be the beginning of modern **electronics**. Fleming also invented the **potentiometer**.

1904 German engineer Christian **Hülsmeyer** invented and patented the first practical **radar** for detecting ships at sea which he called the Telemobiloscope. It consisted of a spark gap transmitter operating in the frequency range of 650 MHz, whose emissions were focused by a parabolic antenna located on the mast of the ship. The receiving antenna picked up the reflected signals and when a ship was detected a bell was automatically rung. Using continuous wave transmissions, it was unable to measure distances. its range was limited to about one mile and at the time neither government nor private companies were interested in it.

1904 Patent granted to Harvey **Hubbell** in the USA for the "separable attachment-plug", the first 110 Volt AC **mains plug and socket**. Still in use today.

It is surprising that we had electric lights and motors, three phase power generation and distribution, cathode ray tubes, x-ray and electrocardiograph machines, alpha, beta and gamma rays, and batteries were over one hundred years old, all before the humble plug and socket were invented.

1904 Taking steam from the local volcanic hydrothermal springs, Prince Piero Ginori **Conti** tested the first **geothermal power generator** at the **Larderello** in Italy, using it to power four light bulbs. Seven years later, the world’s first geothermal power plant was built on the same site.

1905 Annus Mirabilis - Einstein's miraculous year. In those twelve months, 25 year old patent clerk Albert **Einstein,** shook the foundations of classical physics with five great papers that established him as the world's leading physicist.

- Einstein first challenged the wave theory of light, suggesting that light could also be regarded as a collection of particles, now called **photons** whose energy is proportional to the frequency (colour) of the radiation. A photon of electromagnetic energy is considered to be a discrete particle with zero mass and no electric charge and having an indefinitely long lifetime. This helped **Plank**'s revolutionary **quantum theory** to gain acceptance. It was for this contribution to science that Einstein received the Nobel prize in 1921, not for the theory of relativity or $E = mc^2$ as is popularly supposed. See also Hertz **photoelectric effect** (1887)
- The second paper, Einstein's doctoral dissertation, shows how to calculate **Avogadro's number** and the size of molecules and surprisingly is Einstein's most cited work.
- The third paper concerned the Brownian motion of small particles suspended in a liquid for which Einstein derived an equation for the mean free path of the particles as a function of the time. See also **Brownian Motion** (1827)
- In the fourth paper, the first about relativity, Einstein showed that absolute time had to be replaced by a new absolute: the **speed of light**.
- In his last paper that year Einstein asserted the equivalence of mass and energy $\mathbf{E = mc^2}$.

Einstein once said "The hardest thing in this world to understand are income taxes".

1905 The experimental findings of the German physical chemist Julius **Tafel** on the relationship between the internal potentials in a battery and the current flowing were summarised in **Tafel's equation**. It is a special case of the more theoretical **Butler-Volmer equation** (1930) which quantifies the electrochemical reactions in a battery.

1905 H **Piper** in the USA patents the **hybrid electric vehicle (HEV)**, a concept introduced in 1899 by **Porsche** in Germany and in Belgium by **Pieper** in 1900 and later demonstrated by **Krieger** in 1903 in France. A top speed of 25 mph was claimed.

1905 French physicist Paul **Langévin** finally explained the cause of magnetism. He suggested that the alignment of molecular moments of the molecules in a paramagnetic substance were caused by an externally applied magnetic field and that the influence of the magnetic field on the alignment becomes progressively stronger with increasing temperature due to the thermal motion of the molecules. He also suggested that the magnetic moments of the molecule, the magnetic properties of a substance, are determined by the valence electrons. This notion subsequently influenced **Niels Bohr** in the construction of his classic model of the structure of the atom.
Langévin also pioneered the use of high intensity ultrasound for use in sonar applications.

1906 Canadian inventor and eccentric genius Reginald Aubrey **Fessenden** was the first to transmit and receive voices over radio waves, inventing the so called **wireless** which made **broadcast radio** possible. While Marconi's invention was equivalent to Morse's, Fessenden's invention was equivalent to **Bell**'s. Bell superimposed a voice signal onto a DC current whereas Fessenden superimposed the voice signal onto an radio wave (a high frequency AC signal known as the **carrier wave**) varying the amplitude of the radio wave in a process known as **amplitude modulation (AM radio)**.
He offered the rights to the patents which covered his radio broadcasting system to AT&T but they found it was was "admirably adapted to the transmission of news, music, etc." simultaneously to multiple locations, but they decided that it was not yet refined enough for commercial telephone service.

Fessenden was a prolific inventor, with over 500 patents relating to radio and sonar to his name including 5 for the heterodyne principle which made **Armstrong** rich and famous, but he never got the recognition he deserved. He was neither a good businessman nor an accomplished promoter and lost control of his patents and the possible wealth that flowed from them, dying a bitter and forgotten man.

1906 Patent awarded to American engineer Greenleaf Whittier **Pickard** working at AT&T for the **crystal detector** used to detect radio waves. Known as the **cat's whisker** it used the rectifying properties of the contact between a fine wire and certain metallic crystals, previously described by **Braun**, in what we would now call a **point contact diode**. Pickard typically used Silicon Carbide (carborundum) crystals. The same year United States Army General Henry H.C. **Dunwoody** also patented a crystal detector device based on carborundum.

1907 Leo Hendrik **Baekeland** a Belgian immigrant in the USA investigating new materials for electrical insulation invented **Bakelite**, or "Oxybenzylmethylenglycolanhydride" to give it its Sunday name, the first **thermosetting plastic** which was later used to manufacture everything from telephone handsets to costume jewellery.

1907 American inventor Lee **De Forest** invents the **audion** tube (valve). Now called the **triode** it was conceived as an **amplifier** but later used also as a switch. It was the first **active electronic device**.

1907 Henry Joseph **Round** an English radio engineer working for **Marconi** in New York, wrote to the "Electrical World" magazine with "A Note on Carborundum" describing his discovery that the crystal gave out a yellowish light when 10 Volts was applied between two points on its surface and that other crystals gave off green, orange or blue light when excited with voltages up to 110 Volts. He had inadvertently stumbled across the phenomenon on which the **Light Emitting Diode (LED)** depends, but there was not enough light to be useful and silicon carbide being hard to work with and Round's discovery was mostly forgotten. The phenomenon was rediscovered by **Losev** in 1922 and again by **Holonyak** in 1962.

1907 French physicist Pierre Ernst **Weiss** postulated the existence of an internal, "molecular" magnetic field in **magnetic materials** such as iron with molecules forming into microscopic regions he called **magnetic domains** within which the magnetic fields due to atoms are aligned. Under normal conditions domains themselves are randomly oriented and they have no magnetic effect. However, when they are put in a magnetic field, they tend to align themselves with the magnetic field causing the material to exhibit magnetic properties.

The concepts of paramagnetism and diamagnetism were first defined by **Faraday** in 1846. Magnetic properties are now understood to be a result of electric currents that are induced by the movement of the electrons in individual atoms and molecules. These currents, according to Ampere's law, produce magnetic moments in opposition to the applied field. The electron configuration in the atoms determines its magnetic properties whether diamagnetic or paramagnetic.

Diamagnetic materials, when placed in a magnetic field, have a magnetic moment induced in them that opposes the direction of the magnetic field. Paramagnetic behaviour results when the applied magnetic field lines up all the existing magnetic moments of the individual atoms or molecules that make up the material. This results in an overall magnetic moment that adds to the magnetic field. Pierre **Curie** showed that paramagnetism in nonmetallic substances is usually characterized by temperature dependence; that is, the size of an induced magnetic moment varies inversely to the temperature. Weiss's domains apply to **ferromagnetic** substances like iron which retains a magnetic moment even when the external magnetic field is removed. The strong magnetic effect causes the atoms or molecules to line up into domains. The energy expended in reorienting the domains from the magnetized back to the demagnetised state manifests itself in a lag in response, known as **hysteresis**. Ferromagnetic materials lose their magnetic properties when heated, the loss becoming complete above the **Curie temperature**.

1907 After almost 3000 years of use in various forms, the first patent for the process of **silk screen printing** or **serigraphy** (from the Latin "Seri" - silk) was awarded to English printer Samuel **Simon** of Manchester. Although the use of a rubber bladed squeegee to force the ink through the stencil was already known, he is generally credited with the idea of using silk fabric as a screen or ground to hold a tieless stencil. Screen printing derives from the ancient art of stenciling used by the **Egyptians** as early as 2500 B.C. and refined by the **Chinese** in the seventh century A.D.. Screen printing is arguably the most versatile of all printing processes, able to print on any surface, with any shape or contour and any size. Although the silk mesh has been replaced by more durable or stable materials such as polyester and perforated metal screens, the technique is still used extensively in the electronics industry today for printing **thick film** and **thin film** circuits, for printing the etching patterns for **printed circuit board** tracks and for the precision application of conductive and other adhesives for making connections and mounting components on surface mounted printed circuit boards as well as for the conventional printing of logos, designs and text on both components and packaging.

1908 Construction of the first German **pumped storage** power plant and of hydraulic research centre in Brunnenmuehle in Heidenheim by **Voith** Turbo. Since then many more pumped storage systems have been installed throughout the world. The **hydraulic battery**.

1908 Swiss textile engineer Jacques Edwin **Brandenberger** invented **Cellophane**, made from the cellulose fibres of wood or cotton. It is used as a separator in batteries particularly in silver oxide cells.

1909 Danish biochemist Søren Peter Lauritz **Sørensen** introduced the concept of **pH** as a measure of the acidity or alkalinity of a solution.

1909 Hermetically sealed wet battery introduced by **Beautey** in France.

1910 American Robert **Millikan** determined the **charge** on the **electron** by means of his **Oil Drop experiment**.

In 1897 John S.E. **Townsend** one of **J.J. Thomson**'s research students, and in 1903 Thomson himself with H.A. **Wilson** (no relation to the inventor of the "Cloud Chamber"), had measured the charge on the electron with a similar method using a water cloud but their results were inaccurate. Millikan adapted this technique with some ingenious (and some not so ingenious) changes to measure e to within a 0.4% accuracy. A fine mist of oil drops was introduced into a chamber in which the air was ionised by X-rays. From the ionised gas some electrons attach themselves to some of the oil droplets. At the top of the chamber was a positively charged plate with a corresponding negative plate at the base. Charged droplets (with electrons) were attracted upwards to the positive plate while uncharged droplets fell downwards under the influence of gravity. By adjusting the voltage between the plates the electrical field could be varied to increase or decrease the upward force on the charged droplets. The voltage was adjusted so that the charged particles appeared stationary at which point the electrostatic force just balanced the gravitational force. The charge on the electron could then be calculated from a knowledge of the electrical field and the mass of the oil droplet determined by the speed at which it falls. Since the magnitude of the e/m ratio had already been determined by **J.J. Thomson**, the experiment also allowed the **mass** of the **electron** to be determined. From his work we know that the electron has a charge of -1.6 X 10^{-19} Coulombs and a mass of 9.1 X 10^{-31} Kg, which is only 0.0005 the mass of a proton. From this we can derive that a current of 1 Amp (1 Coulomb per second) is equivalent to an **electron flow** of 6.3 X 10^{18} electrons per second.

Although Millikan's method was beautifully simple, his published conclusions did not truly reflect the results of the measurements made. He was selective in choosing the results, discarding two thirds of the measurements made because they did not support his conclusions, at the same time improving the accuracy of the experiment. He was right, but it took others to prove it conclusively.

Millikan initially studied classics and worked as a teacher and administrator. He did not begin to do research seriously until he was almost forty. He eventually was awarded the Nobel prize for his determination of **Planck's Constant**.

1910 William David **Coolidge** working at General Electric in the USA invented the tungsten filament which greatly improved the longevity of the light bulb.

1910 Neon lighting using the techniques discovered by **Plücker** and **Hittorf** and the newly discovered neon gas was patented by French experimenter Georges **Claude**. Substituting different gases allowed a range of colours to be produced. Although the neon lights were used for advertising in France it was not until 1923 that they were brought to the USA by Packard car dealer Earl Anthony.

1911 Superconductivity was first observed in mercury by Dutch physicist Heike Kamerlingh **Onnes** of Leiden University. When he cooled it to the temperature of liquid helium, 4 degrees Kelvin, its resistance suddenly disappeared.

1911 The experiment on radioactivity that contributed most to our knowledge of the **structure of the atom** was done by **Rutherford**, who with **Soddy** had previously identified the **atomic radiation** emitted by Uranium and explained the phenomenon of **radioactive transformation**.
Working at the University of Manchester with his students Hans **Geiger** (later famous for his "Counter") and Ernset **Marsden**, Rutherford bombarded a thin foil of gold with a beam of alpha particles (Helium nuclei) and looked at the beams on a fluorescent screen. They noticed that most of the particles went straight through the foil and struck the screen but some (0.1 percent) were deflected or scattered in front (at various angles) of the foil, while others were scattered behind the foil.
Rutherford concluded that the gold atoms were mostly empty space which allowed most of the alpha particles through. However, some small

region of the atom must have been dense enough to deflect or scatter the alpha particle. He called this dense region which comprised most of the mass of the atom the **atomic nucleus** and proposed the model of an atom with a nucleus and **orbiting electrons**. Awarded a Nobel prize for his work on the structure of the atom, he famously said "The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from the transformation of these atoms is talking moonshine. " If he didn't believe Einstein, he could have at least profited from advice from another of his students, **Niels Bohr** (1913 below).

1911 In an address to the Röntgen Society, Scottish engineer Alan Archibald (A.A.) **Campbell Swinton** described in detail the workings of a proposed all electronic television system using a cathode ray tube scanning an array of photocells onto which the image was projected for the transmitter and another cathode ray tube scanning a fluorescent screen as the receiver. This was at a time when the possibilities of radio communication had just been discovered, radio valves were practically unknown, photocells were most inefficient and vacuum technology was still very primitive. Due to obvious difficulties at the time the system was never constructed. It was left to another Scottish inventor, John Logie **Baird** to demonstrate the first working television system in 1926. It was an electromechanical system based on the **Nipkow disc** image scanning system. Although Baird's system was used in 1929 for the first public broadcasts in the UK, electromechanical systems proved to be a dead end.

1912 **J J Thomson** and Frederick **Soddy** discovered **isotopes** by observing the different parabolic paths traced by ions of different mass when passing through electric and magnetic fields. Soddy formulated the concept of isotopes, for which he was awarded a Nobel Prize in 1921. It states that certain elements exist in two or more forms which have different atomic weights but which are indistinguishable chemically. They used this phenomenon to construct the first **Mass Spectrometer** (then called a parabola spectrograph), a tool that allows the determination of the mass-to-charge ratio of ions and the identification of the different compounds contained in chemical samples. The Mass Spectrometer has since become an ubiquitous research tool in chemistry.

1912 Charles **Kettering** in the USA invented the first practical **self-starter** for automobiles, originally patented by **Dowsing** in 1896. The subsequent adoption by General Motors of battery-started cars provided the impetus for massive growth in the demand for lead acid batteries spawning new developments and performance improvements. See **Willard** 1915.

1912 Australian born Sir William Lawrence **Bragg** working with his father British physicist William Henry Bragg at Cambridge University discovered **X-ray diffraction** and formulated **Bragg Law** to quantify the phenomenon, thus founding the study of **X-ray crystallography**. The process is used to analyse crystal structure by studying the characteristic patterns of X-rays that deviate from their original paths because of deflection by the closely spaced atoms in the crystal. This technique is one of the most widely used structural analysis techniques and plays a major role in fields as diverse as structural biology and materials science. X-ray crystallography is used in battery design to analyse alternative chemical mixes and the associated crystal structures to optimise the physical and chemical characteristics of the active chemical contents in the cells. The ability to study the structure of crystals marked the origin of solid-state physics and provided a vital tool for the development of today's semiconductor industry.

1912 German physicist Max **von Laue** proved that **X-rays** are electromagnetic waves with a wavelength shorter than or of the same order as the separations between the ordered atoms in a crystal by examining the interference or diffraction effects that could be observed when an X-ray beam hits layers of atoms in a crystal. The wavelength observed was about 1000 times shorter than the wavelength of light. Von Laue was given the 1914 Nobel Prize for his discovery of diffraction of X-rays

1912 Scottish physicist Charles Thomson Rees Wilson devised the **Wilson cloud chamber** as a means of making the tracks of ionising radiation visible in order to detect **sub atomic particles** such as protons and electrons and other ionising radiation. It consisted of a closed container filled with a supersaturated vapour such as water in air. When ionising radiation passes through the vapour, it leaves a trail of charged particles (ions) that serve as condensation centres for the vapour which condenses around them. The path of the radiation is thus indicated by tracks of tiny liquid droplets in the supersaturated vapour

1912 Twenty one year old Russian immigrant David **Sarnoff** was working as a telegraph operator at the **Marconi Wireless station** in New York when **SOS** signals from the sinking S.S. Titanic came in from the frozen North Atlantic. Staying at his post relaying messages for 72 hours straight brought him instant fame. The experience convinced him of the potential of radio and he went on to found the **Radio Corporation of America RCA**.

1913 Neils **Bohr** a Danish physicist working under **Rutherford** in Manchester applied **quantum theory** to molecular structure proposing a more detailed **model of the atom** with electrons existing in orbits that had discrete quantised energies, or specific **energy levels**. He proposed that the chemical properties of the element are largely determined by the number of electrons in the outer orbits and introduced the idea that an electron could drop from a higher-energy orbit to a lower one, emitting a **photon** (light quantum) of discrete energy. This became the basis for **quantum mechanics** for which he was awarded a Nobel prize in 1922.
In contrast to his mentor Rutherford, Bohr is quoted as saying "Prediction is very difficult, especially about the future"

1913 Young English Physicist Henry Gwyn Jeffreys **Moseley** working with **Rutherford** at Manchester explained for the first time the fundamental pattern underlying the **periodic table**. Using **X-ray spectra** obtained by **diffraction** in crystals bombarded with cathode rays, he found that the heavier the atomic mass of the element, the shorter was the wavelength and the more penetrating were the X-rays emitted, indicating a systematic relationship between the wavelength of the X-rays and the atomic mass of the element. (X-rays are generated when a focused electron beam accelerated across a high voltage field bombards a stationary or rotating solid target). He determined that the positive charge on the nuclei of the atoms always increases by 1 in passing from one element to the next in the periodic table and he called this the **atomic number**. Moseley's discovery showed that atomic numbers were not arbitrary as had previously been thought, but followed an experimentally verifiable pattern. He predicted the existence of two new elements, now known to be radioactive, non-naturally-occurring technetium and promethium, by showing that there were gaps in the sequence at numbers 43 and 61.

Like many other patriotic youths at the time Moseley volunteered to serve in the First World War and was killed at Galipoli at the age of 27.

1913 Patent filed by Arthur **Berry** for **etched printed circuits** used in heaters. Similar **subtractive techniques** were also proposed by **Littlefield** and E. **Bassist** using photoengraving and electrodeposition of copper but the ideas do not appear to have caught on.

1913 Henry **Ford** introduced the **moving conveyor line** for assembly operations. Also called the **paced production line**, in conjunction with better materials flow to each work place, it enforced work rate and line discipline enabling major efficiency gains to be achieved. It was not popular but the huge reductions in assembly time enabled Ford to pay higher wages. Paced production lines are now the norm for producing high volumes of high labour content products.

1914 Using the photoelectric effect **Millikan** determined **Plank's constant** directly - verifying the 1905 Einstein theory of the photoelectric effect and the quantum nature of light. (After ten years trying to prove Einstein's photon or particle theory that light was wrong, he eventually succeeded in proving it was right.) He was awarded the Noble prize for this work in 1923.

1915 American physicist Manson **Benedicks** discovers the **rectifying** properties of **germanium crystals**, a discovery that will ultimately lead to the development of the "semiconductor chip".

1915 Improvements to automotive lead acid SLI battery reliability and safety introduced by **Willard Storage Battery Company** including rubber plate separators and shortly afterwards hard rubber cases. Previously lead acid battery designs had been diverse and unreliable with cases and separators constructed from a variety of materials such as wood dipped in asphalt, waxed leather, ceramics and glass. For the next 30 years or more, until the availability of easily moulded plastics, the construction of automotive batteries was based on design concepts introduced by Willard.

1915 During the First World War, batteries became essential for powering torches and particularly military field telegraph equipment but the source of pyrolusite from which is derived the manganese dioxide, needed for Leclanché cells, was controlled by the Germans and an alternative had to be found. In response, French physicist Charles **Fery** developed an alternative **air depolarising battery**. The cathode was a large porous carbon pot, only partially filled by the zinc anode and the electrolyte was open to the air. The design essentially diluted the polarisation effect of the hydrogen generated and promoted contact with the oxygen in the air for recombination into water. It was not very efficient but although it was not perfect it served its purpose and 1.5 million were produced. It could be considered the forerunner of the **Zinc-Air battery**.

1915 Western Electric engineer Edwin H. **Colpitts** patented the **push-pull amplifier**. The design used a phase splitter to separate the positive going part of the wave form from the negative going part and amplified the two parts in separate valves (tubes). After amplification the two parts were recombined to reconstitute the waveform. Since two valves were used the design permitted higher power outputs to be achieved and at the same time, because the voltage swing in each valve was lower, the circuit provided linear amplification free from distortion.

1915 American engineer Ralph Vinton Lyon **Hartley** working at Western Electric invents the **variable frequency Hartley oscillator** which can be tuned using a variable capacitor. Oscillation is induced by positive feedback around a valve (tube) amplifier. The frequency of oscillation is determined by two inductors (or a tapped single inductor) and a single capacitor. Modern versions use transistors or operational amplifiers to provide the amplification.

The same year fellow Western Electric engineer E. H. **Colpitts** (see above) invented an alternative oscillator with slightly better frequency stability. It is the electrical dual of a Hartley oscillator using two capacitors and one inductor determine the frequency.

1916 American chemist Gilbert Newton **Lewis** advanced **Frankland**'s theory of valency and established the basis of the theory of **chemical bonding** by proposing that **chemical bonds** are formed between the atoms in a compound because electrons from the atoms interact with each other. He had observed that many elements are most stable when they contained eight electrons in their valence shell and suggested that atoms with fewer than eight valence electrons bond together to share electrons and complete their valence shells.
The compounds used in batteries consist mainly of metal and non-metal atoms held together by **ionic bonding** in which electrons are completely transferred from one atom to another. The atoms losing a negatively charged electrons form positively charged ions, while the atoms gaining electrons become negatively charged ions. The oppositely charged ions are attracted to each other by electrostatic forces which are the basis of the ionic bond. This explains the theory of **dissociation** proposed by **Arrhenius** in 1884.

1916 German physicist Arnold Johannes Wilhelm **Sommerfeld** enhanced the Bohr theory of the **atomic structure** by introducing non-circular orbits, by allowing quantised orientations of the orbits in space, and by taking into account the relativistic variation in the mass of the electron as it orbited the nucleus at high speed. These properties or **quantum states** were characterised by three **quantum numbers** in what is now called the **Bohr-Sommerfeld model** of the atom.

1916 1916 Edwin Fitch **Northrup** working at Princeton University invents the coreless **high frequency induction furnace**.

1916 Metallurgist Jan **Czochralski**, born in Kcynia, Western Poland, then part of Prussia (Germany), working in Berlin accidentally discovered a method of drawing single crystals when when he absent mindedly dipped his pen into a crucible of molten tin rather than his inkwell. On pulling the pen out he discovered that a thin thread of solidified metal was hanging from the nib. Experimenting with a capillary in place of the nib, he verified that the crystallized metal was a single crystal and went on to develop the technology for producing large **single crystals**, still a fundamental process for semiconductor fabrication today.
At the request of the president of Poland, in 1928 he moved back to Poland to take up the post of Professor of Metallurgy and Metal Research at the Chemistry Department of the Warsaw University of Technology where he published many papers. However after World War II he was unjustly accused of aiding the Germans during the war and stripped of his professorship. Although he was later cleared of any wrongdoing by a Polish court, he returned to his native town of Kcynia where he ran a small cosmetics and household chemicals firm until his death in 1953.

The **Czochralski (CZ) method** of growing single crystals was adopted in 1950 by **Bell Labs** and is used today in 95% of all semiconductor production.

1917 American engineer George Ashley **Campbell** awarded patents for **low pass, high pass** and **band pass filters** consisting capacitors and inductors. These **passive electric wave filters** had already been employed for several years in the telecommunications industry for signal conditioning, selection and tuning and similar designs had been developed in Germany by K W **Wagner** in 1915.

1917 **Rutherford** bombarded Nitrogen gas with naturally occurring alpha particles (Helium nuclei) from radioactive material and obtained atoms of an Oxygen isotope and positively charged particles with a higher energy which he called **protons** (Hydrogen nuclei, isolated for the first time). He had **split the atom**, creating the world's first **nuclear reaction**, albeit a weak one. Rutherford had achieved the alchemist's dream of transmuting matter, which led to the work on **nuclear fission**.

Rutherford did not publish the results of this experiment until two years later in 1919. He continued his investigations with **Cockcroft** and **Walton** who started work in 1928 on a controlled source of high energy particles which enabled them probe deeper into the atomic structure.

1918 American engineer and inventor Edwin Howard **Armstrong** patented the **superheterodyne** radio receiver solving the problem of providing a wide tuning range and high selectivity between stations. This was achieved by using a variable frequency local oscillator or frequency changer to shift the signal (carrier wave plus sidebands) of the desired transmitter to a convenient fixed intermediate frequency (IF). Tuning takes place in a separate narrow band IF amplifier which only needs to be tuned to a single frequency.

German engineer Walter **Schottky** also independently invented a superheterodyne radio receiver the same year.

A simple version of the idea had been used by **Fessenden** in 1901 but he had not developed it. He did however give the circuit its name from the Greek *heteros* (other) and *dynamis* (force). Until the digital age and phase locked loops, the superheterodyne principle was used in 98% of all radios world wide.

1918 A. M. **Nicholson** working at Bell Labs patents the **crystal oscillator**. When a varying signal is applied across the crystal it expands and contracts in sympathy. The crystal oscillator circuit sustains oscillation by taking a voltage signal from the crystal, amplifying it, and feeding it back to the crystal which resonates at a certain frequency determined by its cut and size. Today more than 2,000,000,000 quartz crystals are produced annually for use in electronic circuits needing precise frequency control including radio tuners, mobile phones, computers, clocks and watches.

1918 Max **Schoop** produced high current **printed circuit boards** with heavy tracks for high power vacuum tube circuits using **metal deposition** by flame spraying through a mask. While successful, like **Berry**'s ideas before him, they were not taken up by others.

1919 The **flip-flop** or **bi-stable latch circuit** a basic building block in all **digital** computers and **logic circuits** was invented by British engineers William Henry **Eccles** and F.W. **Jordan** working at the government's National Physical Laboratory. Originally implemented with triodes, now with transistors **(diagram)**, it can remember two possible conditions or states and thus is able to store a single bit of information or a **binary digit**, thus enabling computers to count. This was the circuit chosen in 1958 by Robert **Noyce** for the first planar Integrated Circuit.

Eccles and Jordan were not Americans as reported on many US based web sites. Another internet myth. Eccles did pioneering work on radio propagation and was a Fellow of the Royal Society (FRS). He rose to be President of the Physical Society from 1928 to 1930, and President of the Institute of Electrical Engineers (IEE) in 1926. Jordan faded into obscurity.

1919 The **Electret**, the electrostatic equivalent of the permanent magnet, was discovered by Mototaro **Eguchi** in Japan. Electrets are dielectric materials that have been permanently electrically charged or polarised. They are produced by heating certain dielectric materials to a high temperature and then letting them cool while immersed in a strong electric field. The materials are composed of long molecule chains, each with an **electric dipole moment** which can be formed into **electrostatic domains** similar to the **magnetic domains** found in magnets. Electret foils are commonly used in microphone transducers since they do not require a polarising voltage to be applied as in "condenser" microphones.

1919 The **tetrode** valve was invented by Walter Schottky who discovered that by placing a grid between the anode plate and the control grid of a triode valve, the grid-plate capacitance was reduced to almost one-hundredth of that in the triode. The second grid acted as a screen to prevent the anode voltages from affecting the control grid and eliminated instability (oscillation) caused by anode-grid feedback in the triode valve.

1920 The first regular commercial radio broadcasts by **KDKA** in Pittsburgh. By the end of 1922 a further 563 licensed A.M. radio stations are operating.

1921 12% of British homes wired for electricity

1920's Diesel electric locomotives first introduced with **electric drives** providing the transmission mechanism eliminating the need for a clutch and a gearbox. (Electric drives provide maximum torque at zero speed. Internal combustion engines can only provide driving torque when they are running at speed)

1922 The **BBC** was formed in the UK by a group of leading "**wireless**" manufacturers including **Marconi** and started a **radio broadcast** service. Widespread radio broadcasting started around the same time in many countries throughout the world bringing wireless into the heart of many homes and with it a new demand for batteries to power them.

1922 Light emission from silicon carbide diodes was rediscovered in the Soviet Union by self taught Oleg V. **Losev**. He produced a range of **high frequency oscillating, amplifying and detector diodes** using zinc oxide and silicon carbide crystals about which he published 16 papers on the underlying theory of operation and was awarded ten patents on **Light Emitting Diodes (LED)**'s, **photodiodes** and **optical decoders** of high frequency signals.
Even more amazing was his discovery of the **negative resistance** (dI/dV) characteristic that can be obtained from biased point-contact zincite (ZnO) crystal diodes and the possibility of using this negative resistance region to obtain amplification, anticipating the tunnel diode. See negative resistance characteristic. He used these properties to construct fully **solid-state RF amplifiers**, detectors and oscillators at frequencies up to 5MHz a quarter century before the invention of the transistor.
He designed and constructed over 50 radio receivers, incorporating his own tuning, heterodyning and frequency converting circuits and built a production line to produce his **cristadyne** radio receivers, powered by 12 Volt batteries, thirty years before the transistor radio. Interstage interaction inherent in using two-terminal devices to obtain gain and adjusting the **cat's whiskers** were problematical but the radios worked. These problems together with the difficulties of obtaining zincite which was found in commercially significant quantities in only two mines, both in New Jersey, USA led to Losev eventually abandoning the crystadyne.

Losev starved to death during the siege of Leningrad in 1942 and the original records of his works were lost.

1922 After the 1917 Russian revolution, naval engineer Nicholas **Minorsky** emigrated to the USA where he worked with Steinmetz. Using his knowledge of automatic steering of ships, in 1922 he published a paper "Directional stability of automatically steered bodies", outlining the principles of **3 term controllers**, the basis of modern PID control systems.

1922 German organic chemist Hermann **Staudinger** published his theories on **polymers** and **polymerisation**. He showed that natural rubbers were made up of long repetitive **chains of monomers** that gave rubber its elasticity and that the high polymers including polystyrene manufactured by the thermal processing of styrene were similar to rubber. Staudinger won the Nobel Prize for Chemistry for his research. **Polystyrene** was originally discovered in 1839 by German apothecary Eduard **Simon** however he was not aware of its significance. It was first produced on an industrial scale by IG-Farbenindustrie in 1930

1923 The **Marconi Company** in Britain claimed to have made the first practical **hearing aid** called the **Otophone**. It used a carbon microphone and valve (vacuum tube) amplifier but with batteries it weighed an unpractical 7 Kg. It was not until 1953 with the advent of transistors and button cells that **electronic hearing aids** became truly practical.

1923 Quality engineers from the Western Electric Company working on **sampling inspection** theory developed graphs showing the probabilities of acceptance and rejection for different **sampling plans**. They identified the concepts of **Consumer's Risk**, the probability of passing a lot submitted for inspection which contains the tolerated number of defectives and **Producer's Risk**, the probability of rejecting a lot submitted for inspection which contains the tolerated percentage of defects. In 1926 they produced the first set of **Sampling Inspection Tables** for single and double sampling followed in 1927 by tables for determining the **Average Outgoing Quality Limit (AOQL)**. The tables were published by Harold F. **Dodge** and Harry J. **Romig** in 1944 however these sampling and control techniques had already found wider use during World War II when standard military sampling procedures for inspection by attributes were developed by the US military and eventually published as **Mil Std 105A** in 1950.

The tables and techniques were designed to facilitate better production control, more efficient inspection and to avoid disputes and were very effective in achieving these goals over many years. Unfortunately they also encouraged the notion that faults were inevitable and the idea of an **acceptable quality level** placed a limit on aspirations to do better, effectively giving a licence to ship a few defects so long as the AOQL was acceptable. An example of "The Law of Unintended Consequences". The danger of these attitudes was finally realised in the 1980's when the public noticed that the Japanese, following principles introduced by W. E. **Deming**, coupled with Japanese work ethics, produced products which were significantly better than western offerings. Working to **Six Sigma** quality standards has been the West's response to the Japanese challenge of **TQM**.

"Statistics means never having to say you're certain" - Anon

1923 Danish chemist Johannes **Brønsted** and simultaneously British chemist Thomas **Lowry** proposed the Brønsted - Lowry concept of **Acids** and **Bases** which states that: An acid is a molecule or ion capable of donating a proton (That is a hydrogen nucleus H^+) in a chemical reaction , while a base is a molecule or ion capable of accepting one. More simply: An acid is a proton donor and a base is a proton acceptor.
The same year **Lewis** proposed a more generalised concept which states: An acid is a molecule or ion that can accept a pair of electrons while a base is a molecule or ion that can donate a pair of electrons. This explains why metal oxides are basic since the oxide ion donates two electrons while non-metal oxides which accept two electrons to share with the non-metal atom are acidic.

1924 German psychiatrist Hans **Berger** was the first person to prove the existence of so called **brain waves**, electric potentials or voltage fluctuations in the human brain, using an an **electroencephalograph** to detect and amplify the signals. He experimented by attaching electrodes to the skull of his fifteen year old son Klaus, recording the first human **electroencephalogram (EEG)**.

1924 French aristocrat who came to physics late in life, Prinz Louis-Victor Pierre Raymond, duc **de Broglie**, speculated that nature did not single out light as being the only matter which exhibits a **wave-particle duality**. He proposed that since light waves could be considered as particles the converse should be true and ordinary ``particles'' such as electrons, protons, or bowling balls could also exhibit the characteristics of waves.
He was awarded the Nobel Prize in 1929 for his work on subatomic particles.

1924 The modern, **moving coil, direct radiator, loudspeaker** patented by Western Electric (Bell Labs) engineers Chester W. **Rice** and Edward Washburn **Kellogg**.

1924 The **ribbon microphone** and its converse the **ribbon loudspeaker** were invented by German engineers Walter **Schottky** and Erwin **Gerlach** working at Siemens. The ribbon microphone was constructed from an extremely thin concertina ribbon of aluminium placed between the poles of a permanent magnet.

1925 Electrical recording using a microphone, an amplifier using **De Forest's** **Audion vacuum tube** (valve) and an electrical disc-cutting head, in a system invented the previous year by Joseph P. **Maxfield** and Henry C. **Harrison** of Western Electric, was adopted by the Columbia and Victor record companies. **Electrical playback** also became available the same year using amplifiers and the **Rice-Kellogg** loudspeaker.
What is surprising is that the basic technologies for implementing electrical recording and play back had been available in the telephone industry since 1877 when **Edison** invented the **phonograph** but for almost fifty years the record industry had persevered with Edison's system of direct acoustic recording on to wax cylinders or discs using large recording horns which both limited and dominated the recording environment. Similarly playback was had remained mechanical over the same period using clockwork motors, acoustic pick-ups and clumsy horns which gave out limited sound volume.

1925 Between 1925 and 1935 American engineer and politician Vannevar **Bush** and colleagues developed a series of **analogue computers** which they called **differential analysers**. They were capable of solving differential equations with up to eighteen independent variables and were based on interconnected mechanical integrators constructed from gears and mechanical torque amplifiers with the output represented by distances or positions. The 1935 version weighed 100 tons and contained 2000 vacuum tubes, 150 motors, thousands of relays and 200 miles of wire. Processing analogue data is a key requirement of modern control systems, however analogue values can now be represented electrically and processed in linear integrated circuits or converted to digital form for manipulation by microprocessors.

1925 Swiss theoretician Wolfgang **Pauli** explained why electrons orbiting an atomic nucleus do not all fall into their lowest energy state due to attraction from the positive protons in the nucleus. He proposed that besides orbiting the atomic nucleus, as in the three state model proposed by **Neils Bohr** and Arnold **Sommerfeld**, the electrons also have **spin properties**. Thus the electron can have four **quantum states** characterised by

4 **quantum numbers** which define, the distance of the electron from the nucleus, its kinetic energy (based on its angular momentum), its magnetic moment (based on the azimuth angle of the plane of the orbit) plus the intrinsic magnetic moment of the electron itself due to its spin. He further proposed the principle that no two electrons in an atom can occupy the same quantum state, now known as the **Pauli Exclusion Principle**. This principle also provided the theoretical basis for the **Mendeléev's Periodic Table of Elements**.
Pauli was awarded the Nobel Prize in 1945 for his discovery of a new law of Nature.

One of the giants of twentieth century theoretical physics Pauli was notorious for his rudeness. He was also known for the "Pauli Principle" which predicted disaster for any piece of apparatus with which he was involved.

1925 German physicist Werner **Heisenberg** proposed a new model for the structure of the atom with different quantised energy states represented by frequencies and intensities. At the suggestion of Max **Born** these were incorporated into matrices. Known as **Matrix Mechanics** theory, it was a mathematical abstraction, but based on observable qualities of the atom, since current methods at describing the atom with physical analogues of orbiting electrons could not account completely for its behaviour.
He was awarded the Nobel Prize for physics in 1932 for this work.

Heisenberg was appointed to be head of Germany's atomic weapons programme during World War II and although, through the pioneering work of **Szilard**, **Hahn** and **Strassmann** on nuclear fission, Germany was ahead of the Allies before the war, by 1945 they were still a long way from being able to produce an atomic bomb and never even achieved a chain reaction.

1925 Charles **Ducas** described a variety of practical ways for manufacturing printed circuits including etching, electroplating and printing with conductive inks. He also proposed **multilayer circuit boards** and showed how to implement connections between the layers.

1926 Frenchman Cesar **Parolini** devised improved **additive printing and plating techniques** for printed circuit manufacturing methods, some of which had been described years before, but not implemented by **Edison**.

1926 Waldo L. **Semon** an American chemical engineer invented plasticised **poly vinyl chloride (PVC)**. The plasticisers are smaller, oily molecules interwoven with the long polymer chains which allow them to slide over eachother and give the plastic its characteristic flexibility. Without these plasticiser additives PVC would be too brittle. Originally discovered by **Baumann** in 1872 PVC is now used extensively for **insulating** wires and cables.

1926 German engineers **Eckert** and Karl **Ziegler** patent first commercial **injection moulding machine**.

1926 Building on **de Broglie**'s wave - particle duality hypothesis Austrian physicist Erwin **Schrödinger** formulated a theory for the behaviour of atomic particles which has the same central importance to **Quantum Mechanics** as Newton's laws of motion have for the large-scale phenomena of classical mechanics. **Schrödinger's Wave Equation** was proposed as an alternative to **Heisenberg's Matrix Mechanics**. It describes the atom in the form of the probability waves (or wave functions) that govern the motion of small particles, and it specifies how these waves are altered by external influences. He realized that the possible orbits of an electron would be limited to those accommodating standing waves, that is, with an exact number of wavelengths. This permits only a limited number of possible orbits and no possible orbits between them. Schrödinger's theory of **Wave Mechanics** explained the hitherto inexplicable behaviour of atomic particles by considering them as waves not particles and the wave equation predictions were borne out by experimental results. He considered his model closer to classical physical theory and less of an abstraction than Heisenberg's model. Paul **Dirac** later proved that these two models were equivalent.

Schrödinger contributed to many branches of physics including quantum theory, optics, kinetic theory of solids, radioactivity, crystallography, atomic structure, relativity and electromagnetic theory. In 1935 he published the famous **Schrödinger's cat paradox** which was designed to illustrate the absurdity of the probabilistic notion of quantum states. This was a thought experiment where a cat in a closed box either lived or died according to whether a quantum event occurred. The paradox was that both universes, one with a dead cat and one with a live one, seemed to exist simultaneously until an observer opened the box. In his later years he applied quantum theory to genetics. He coined the term "**Genetic code**"and published an influential book "What is Life" which inspired **Watson and Crick** in their search for the structure of DNA. He also studied Greek science and philosophy and published his thoughts in his book "Nature and the Greeks".
He was awarded the Nobel Prize for physics in 1933.

What has Schrödinger got to do with batteries?
Schrödinger's wave mechanics provided the foundation, built on by **Heisenberg**, **Dirac** and others, for explaining the behaviour of electrons, nuclei, atoms, molecules and **chemical bonding**, fundamental building blocks or processes used in galvanic cells, as well as **nanotechnology** and the phenomena of **nuclear fusion** and **superconductivity**, processes used in the generation and distribution of electric power. Quantum mechanics also represents behaviour of electrons and "**holes**" (the absence of electrons) in **semiconductors** and the process of **electron tunneling** used in **Scanning Tunneling Microscopes** and other electronic devices. For the future, research into the possibilities of **quantum computers** whose bits can be both 0 or 1 at the same time, depending on the electron spin, performing calculations at unprecedented speed are also founded on the quantum theories of Schrödinger, Heisenberg, Dirac and their successors.
It was almost forty years before before the principles demonstrated by Volta in his voltaic pile were successfully put to use by the **telegraph** pioneers in commercial products. In the case of Faraday's **motor**, it was almost sixty years before a market was created. Watch out for Schrödinger's kittens.

A man of many accomplishments Schrödinger's life was both colourful and complicated. He had an informal manner and throughout his life he travelled with walking boots and rucksack which raised a few eyebrows at the many conferences he attended. He served in Italy and Hungary during the First World War. Later he was an opponent of Nazi rule in Germany which brought him several brushes with authority. As an eminent physicist he also received many offers of positions in the worlds best universities and at various times he help posts at Graz, Berlin, Breslau, Zurich, Oxford, Princeton, Edinburgh, Rome, Dublin, Gent and Vienna. His relationships with women were however even more wide-ranging. He had numerous lovers with his wife's knowledge (even more Schrödinger's kittens) and she in turn was the lover of one of Schrödinger's friends. While at Oxford he brought his colleague Arthur March from Germany to be his assistant since he was in love with March's wife who was pregnant with his child and he lived openly with his new daughter and two wives one of whom was still married to another man. During his time in Dublin he

fathered two more daughters with two different Irish women.
And he made time to do a little physics....

1926 German physicist Max **Born** working at Cambridge found a way to reconcile particles with waves by treating Schrödinger's wave as the probability that an electron will be in a particular position.

The singer **Olivia Newton-John** is a grand-daughter of Born.

1926 German professor of physics at Leipzig University, Julius Edgar **Lilienfeld** emigrated to the USA and filed a patent for what would today be called a **field effect transistor**. It consisted of a semiconducting compound sandwiched between two metal plates, one of which was connected to a current source and the other connected to the output. The resistance of the semiconductor between the plates could be varied by means of a variable electric field created across it by a control signal connected to a third plate at the side of this sandwich and insulated from it. It worked in a way analogous to a vacuum tube and in 1930 Lilienfeld was granted a patent for "A method and apparatus for controlling electric currents". Other than Lilienfeld, nobody at the time seems to have recognised the device's potential and it faded into obscurity until it was rediscovered by William **Shockley**'s patent attorneys, much to Shockley's chagrin when he independently conceived a similar device 20 years later.

1927 **Heisenberg** discovers the **Uncertainty Principle**. It is impossible to determine the position and momentum of a particle simultaneously. The more accurate one is measured, the more inaccurate the other becomes.

Einstein was very unhappy about this apparent randomness in nature. His views were summed up in his famous phrase, "God does not play dice".

1927 British physicist George Paget **Thomson**, son of **J.J. Thomson**, discoverer of the electron, working with Alexander **Reid** at Aberdeen University and simultaneously and independently, Americans Clinton Joseph **Davisson** working with Lester Halbert **Germer** at Western Electric Labs, confirmed **de Broglie**'s hypothesis of the **wave particle duality of the electron**. Thomson created transmission interference patterns by passing an electron beam through a thin metal foil and Davisson created diffraction patterns of electron beams reflected from metallic crystals, both confirming the wave nature of the electron.
Thomson and Davisson were awarded the Nobel Prize for physics in 1935.

1927 German physicist Friedrich **Hund** was the first to notice the possibility of the phenomenon of **quantum tunneling** which he called "barrier penetration" a process by which a particle can appear to penetrate a classically forbidden region of space passing from point A to point B without passing through the intermediate points. This is a manifestation of **de Broglie's wave - particle duality theory** with the electron acting like a wave rather than a particle. The phenomenon can be characterised by **Schrödinger's wave equation** which tells us that the energy associated with an electron is not discrete but has a probabilistic level. As a consequence a certain number of electrons will have more than enough energy to jump an energy gap that would normally be too wide. The effect is that electrons appear to tunnel through a barrier which we would normally expect bar them.

1927 In the USA a Lead Acid car battery cost $70 while a typical car cost $700. Today a car battery still costs $70 while car prices have skyrocketed by comparison.

1927 Invention and patent application by French company **Chauvin Arnoux** for the "Contrôleur Universel", the forerunner to the **Multimeter**. Despite this patent, the invention was to become copied throughout the world.

1927 In the first technical analysis of a **closed loop control system**, American engineer Harold Steven **Black** working at Bell Labs demonstrates the utility of **negative feedback** in the design of telephone repeater amplifiers to reduce distortion. He thus established the theoretical basis of modern **feedback control systems**.

1927 Generic patent for **flexible printed circuits** as well as **three dimensional circuits** and **printed inductors** by applying conductive materials to a flexible substrate was published by Frederick **Seymour**.

1927 Mormon farm boy from Idaho, Philo Taylor **Farnsworth** conceived the idea of the world's first practical all electronic television system while still in high school. An electronic system had been proposed earlier by **Campbell Swinton** but due to the primitive state of the technology at the time it was never built. Farnsworth built a working system using the **Farnsworth orthicon** or **image dissector tube** and patented his design in 1927 while still only 21 and successfully fought off the patent claims from the mighty RCA. Nevertheless despite paying royalties to Farnsworth, RCA ultimately found ways around the patents and promoting their own man, **Zworykin**, as the originator of the television system they finally put Farnsworth out of business. Like **Armstrong** who had similar battles with RCA, Farnsworth's private life suffered and he became an embittered alcoholic in his early 30's. He spent much of his later life and all of his money in a fruitless pursuit of nuclear fusion.

1927 The **Quartz Clock** invented by Canadian born Warren **Marrison** working at Bell Labs. He demonstrated the superior accuracy of clocks using **crystal controlled oscillators** kept in time by the regular vibrations of a quartz crystal. Initially they were used for precise telecommunications **frequency standards** but today they are found in every battery powered **quartz watch** and they provide the microprocessor system clock in every personal computer.

1928 British physicist Paul Adrien Maurice **Dirac** working on **quantum field theory** at the Cavendish Laboratory in Cambridge combined the theories of **quantum mechanics** of **Bohr** and **Pauli** with **Maxwell's electromagnetic field theory** to model the properties of the electron. He introduced the concept of special relativity and **electron spin**, which gave the electron its internal magnetic properties and which Schrödinger had not been aware of, into Schrödinger's wave equation to develop the **Dirac equation** which was consistent with both **Heisenberg's matrix mechanics** and **Schrödinger's wave theory**. Dirac's model could treat the electron as either a wave or a particle and still get the right answers. It marked the beginning of **Quantum Electrodynamics - QED**.

In 1931, Dirac used his equation to predict the existence of a particle with the same mass as the electron but with positive rather than negative charge. This "**anti-particle**", now called a **positron**, was detected by American physicist Carl **Anderson** in 1932 and all particles are now known to have anti-particles.
Dirac shared the Nobel Prize for physics with Schrödinger in 1933.

Unlike Schrödinger, Dirac's shyness was legendary. When informed that he had won the Nobel Prize he told Rutherford that he did not want to accept it because he disliked publicity. Rutherford told him that refusing the prize would bring even more publicity!

1928 Swedish born American engineer Harry **Nyquist** formulates the **Sampling Theorem** which states that a signal can be exactly reproduced if it is sampled at a frequency F, where F is greater than twice the maximum frequency in the signal. Very important for specifying the **sampling rate** in monitoring and control systems. Nyquist went on to develop **stability criteria** for feedback control systems.

1929 The **kinescope**, a cathode-ray tube with all the features of modern **television picture tubes** invented by Russian born American, Vladimir **Zworykin**, working for RCA. In 1923 while working at Westinghouse, Zworykin applied for a patent on the **iconoscope**, a tube based on **Campbell-Swinton**'s proposal of 1911, designed to create the images in his early **television cameras** but it was not used commercially and the patent was not granted until 1938. Zworykin was told by Westinghouse"to find something more useful to work on". The imaging technology on which television cameras were based is in fact descended from **Farnsworth's image orthicon** but RCA's PR machine claimed that Zworykin laid the foundations of today's television systems in 1923, ignoring the contributions of **Farnsworth**, the farm boy from Idaho who is almost forgotten today.

1930 The works of British physical chemist John Alfred Valentine **Butler** and German surface chemist Max **Volmer** on the theoretical basis of **kinetic electrochemistry** were summarised in the fundamental **Butler-Volmer equation**. It shows that the current flowing at an electrode is the sum of the anodic and cathodic contributions. It is also directly proportional to the area of the electrodes and increases exponentially with temperature.

1930 Russian Wladimir **Gusseff** invents **Electro-Chemical Machining (ECM)** using **electrolytic erosion**, a galvanic process essentially the reverse of electroplating which allows the machining of complex shapes in very hard metals. The work piece forms the anode and the shaped tool forms the cathode and they are supplied with a low DC voltage of about 40 Volts. Electrolyte is pumped through the gap between the tool and the work piece and metal is removed from the work piece in the vicinity of the tool by **galvanic action** as in a battery. The flowing electrolyte removes the dissolved metal so there is no tendency for it to be deposited on the cathodic tool.

Note This is different from the more common machining process known as **Spark Erosion** or **Electro-Discharge Machining (EDM)**. In this process the work piece and the tool are immersed in a bath electrolyte, however the gap between the tool and the work piece is fed with a high frequency pulsating voltage which creates a spark across the gap which in turn vapourises the metal of the work piece in the proximity of the tool. It was invented by Russian brothers B.R. and N.I. **Lazarenko** in 1943.

Both of the above processes are used to make the intricate shapes used in injection moulding tools.

1930 **Lilienfeld** gave a paper on **electrolytic capacitors** before the American Electrochemical Society in which outlined the fundamental theories and practice for the design of these components, still in use today.
Electrolytic capacitors have a very high capacitance per unit volume allowing large capacitance values to be achieved making them suitable for

high-current and low-frequency electrical circuits. The construction is similar to a **spiral wound battery** with two conducting aluminium foils, one of which is coated with an insulating oxide layer which acts as the dielectric, and a paper spacer soaked in electrolyte, all contained in a metal can. The aluminium oxide dielectric can withstand very high electric field strengths, of the order of 109 volts per metre, before break down. This allows the use of very thin dielectric layers to be used and this in turn permits a much larger area of the capacitive plates to be accommodated within the space inside the case. These characteristics enable very high capacitance values to be achieved.

The foil insulated by the oxide layer is the anode while the liquid electrolyte and the second foil act as cathode. They are thus polarized and so must be connected in correct polarity to avoid breakdown.

Electrolytic capacitors can store a large amount of energy and are often used in battery **load sharing** applications to provide a short term power boost. See also **Supercapacitors** and **Alternative Energy Storage Methods**.

1931 Wallace Hume **Carothers** working at DuPont labs created **Neoprene** the first successful **synthetic rubber**. Neoprene's combination of properties, resistance to chemicals, toughness and flexibility over a wide temperature range made it suitable for the design of pressure vents which facilitated the construction of recombinant batteries and for gaskets used in battery enclosures. Searching for synthetic fibres Carothers also invented **Nylon** in 1935, now also used to produce a wide range of injection moulded components from containers to gears. In the USA, nylon stockings went on sale for the first time in 1940 and four million pairs were sold in the first few hours.

Carothers was a manic depressive alcoholic who, despite his great achievements, considered himself a failure. He founded and was head of Du Pont's research group working on polymers and polymerisation which was one of the most successful groups in the history of polymer science. He committed suicide in 1937 at the age of 41 by taking cyanide a year after his marriage and the untimely death of his sister.

1931 The portable **Metal Detector** patented by American engineer Gerhard **Fischar**. Metal detectors use a variety of methods to detect small changes inductance or perturbations in the local magnetic field when the detector is near to a metal object. See also Alexander Graham **Bell's detector**.

1931 Irish chemical engineer James J. **Drumm** introduces the alkaline Nickel Zinc **Drumm traction battery** after five years of development. A variant of the **Michaelowski** chemistry, they had a cell voltage of 1.85 volts and charge / discharge rates 40% higher than Nickel Iron cells with which they were intended to compete but they suffered from a low cycle life and high self discharge rate. Drumm built four trains to use his batteries but with the outbreak of World War II it became impossible to obtain both orders and raw materials and the company folded in 1940.

1931 French engineer H. **de Bellescize** applied for a UK patent for an improved **homodyne** radio **tuning circuit**. It was the first **automatic frequency control (AFC)** system and the first circuit to incorporate the basic features of a **phase locked loop (PLL)**. The following year de Bellescize published a description of his design in "Onde Electrique", volume 11, under the title "La Réception Synchrone". The original homodyne receiver was designed in 1924 by a British engineer named F.M. **Colebrook** in an attempt to improve on **Armstrong**'s **superheterodyne** receiver. Colebrook's design mixed the received signal with a locally generated sine wave at the same frequency as the carrier wave to extract the signal from the carrier in a simple detector - essentially a **zero intermediate frequency (IF)**. De Bellescize improved on this by detecting any difference between the received carrier frequency and the local oscillator frequency and using the difference signal to adjust the oscillator frequency till it matched exactly the carrier frequency thus ensuring perfect synchronisation of the two signals and the desired zero IF. Further improvements to the design were made by british engineer D.G. **Tucker** and others and the tuner was renamed the **synchrodyne**.

The phase locked loop (PLL) is now a fundamental building block in synchronisation and control circuits and complete complete PLL circuits are available in low-cost IC packages.

1931 English engineer Alan Dower **Blumlein** invented **stereo sound**. A prolific inventor Blumlein made many advances in the field of acoustics and made significant contributions to Britain's first all electronic television service. During the war years he applied his considerable skills to Radar design. He died in a plane crash in 1942 at the age of 38 while testing the H2S Airborne Radar equipment for which he had designed many of the circuits. He was awarded 132 patents in his short life.

1932 German electrical engineers Max **Knoll** and Ernst August Friedrich **Ruska** invented the first **transmission electron microscope (TEM)**. One of the first applications of **quantum mechanics** theory, it depends on wave properties of the electron rather than it's particle properties. Instead of a light beam, it used an electron beam which has a wavelength much shorter than a light beam and can thus provide a much higher resolution. Focusing was by means of magnetic coils acting as lenses and by 1933 a magnification of 7000 times was achieved, far in excess of what was possible with visible light. The beam is detected after passing through a very thin specimen to create an image. It is now an essential tool for investigating the structure of materials.

Fifty four years later Ruska was belatedly awarded a Nobel Prize jointly with **Binnig** and **Rohrer** in1986 in recognition of his fundamental work on electron optics and the invention of the electron microscope.

Knoll went on to invent the **scanning electron microscope (SEM)** in 1935 however the modern SEM was invented by **Oatley** in 1952.

See also **STM**

1932 First practical **Fuel Cell** system (Alkaline with porous electrodes) demonstrated by English mechanical engineer Francis Thomas **Bacon**, a direct descendant of **Sir Francis Bacon**, the 17th century philosopher.

1932 The Cavendish Laboratory's annus mirabilis. English engineer and physicist John Douglas **Cockcroft** and Irish physicist Ernest Thomas Sinton **Walton**, working under **Rutherford** at the Cavendish Laboratory, constructed the world's first **nuclear particle accelerator** for investigating atomic structures, now known as the Cockcroft-Walton accelerator, or more colourfully as an **atom smasher**. It was a 700,000 Volt **linear accelerator** which they used to bombard a Lithium target with protons (Hydrogen nuclei). Like many UK university experimenters at the time they had to improvise because of a shortage of resources, using amongst other things car batteries, and for the glass cylinders surrounding the electrodes they used glass tubes from petrol pumps they used Harbutt's plasticine to seal the joints in the vacuum tubes. Very high energies were needed to overcome the repulsion of the positively charged protons by the positively charged Lithium nucleus. The Lithium nucleus contains 3 protons and 4 neutrons. The high energy proton bombardment caused the Lithium nucleus to disintegrate into 2 alpha particles (Helium nuclei), each composed of 2 protons and 2 neutrons. This was the first disintegration of an atomic nucleus by controlled, artificial means, the first artificial nuclear reaction not utilizing radioactive substances, the first use of a particle accelerator to **split the atom** and the first artificial **transmutation** of a metal into another element.

In fact Rutherford had actually already split the atom in 1917 using a radioactive source, however he had merely knocked a proton out of the nucleus. Cockcroft and Walton had actually split it in two.

The speed of the resulting helium nuclei was measured and the kinetic energy calculated. It was found to be equivalent to the reduction in the combined mass of the resulting helium nuclei from the combined mass of the original lithium and hydrogen nuclei. This was the first verification of **Einstein's law**, **$E = mc^2$**.

The "Daily Express" headline on the news of their success was "The Atom Split, But World Still Safe".

Cockcroft and Walton were awarded the Nobel Prize for physics in 1951.

1932 34 Years after the discovery of the electron and the proton, English physicist James **Chadwick** another of Rutherford's students working at Cambridge University finally isolates the **Neutron** confirming Rutherford's predictions of a heavy neutral particle twelve years earlier. Physicists soon found that the neutron made an ideal "bullet" for bombarding other nuclei. Unlike charged particles, it was not repelled by similarly charged particles and could smash right into the nucleus. Before long, neutron bombardment was applied to the uranium atom, splitting its nucleus and releasing the huge amounts of energy predicted by Einstein's equation **$E = mc^2$**. See Fermi (1942)

1932 Within seven months of the discovery of the neutron, Hungarian physicist Leo **Szilard** conceived of the possibility of a controlled release of atomic power through a multiplying neutron **chain reaction** and that this could be used to build a bomb. He fled Germany in 1933 to escape Nazi persecution and in 1934 filed a patent application for the **atomic bomb**, outlining the concept of using neutron induced chain reactions to create explosions and the key concept of the **critical mass**.

Fearful of German intentions with **nuclear weapons** and disturbed by the lack of American action, in 1939 Szilard persuaded Albert **Einstein** to write to President **Roosevelt**, urging him to initiate an American atomic weapons programme. He was rewarded for his pains by Major General Leslie **Groves**, leader of the Manhattan Project designing the atomic bomb, who in 1943, forced Szilard to sell his atomic energy patent rights to the U.S. government.

In like manner in 1942 the Russian nuclear physicist Georgy Nikolaevich **Flerov** noticed that articles on nuclear fission were no longer appearing in western journals from which he concluded that research on the subject had become secret, prompting him to write to Premier Joseph **Stalin** insisting that "we must build the uranium bomb without delay." Stalin took the advice and appointed Igor Vasilevich **Kurchatov**, director of the nuclear physics laboratory at the Physico-Technical Institute in Leningrad, to initiate work on Russia's bomb. Their first nuclear bomb was finally tested on 29 August 1949 near Semipalatinsk on the steppes of Kazakhstan. Flerov and Kurchatov both received the Soviet Union's highest award, the title of Hero of Socialist Labour and the Gold Star medal.

1932 Just when we thought we had an elegant and simple explanation of the **structure of matter** with three **sub-atomic particles**, a nucleus of protons and neutrons with electrons orbiting around it, along came quantum mechanics in the 1920's and shook the foundations of physics. But it didn't end there, the detection in 1932 by **Anderson** of the positron predicted by **Dirac** indicated the existence of a lower level of **elementary**

particles which make up the basic building blocks of the sub-atomic particles. It initiated the discovery over the next 50 or more years of whole families of elementary particles including **Leptons, Quarks, Bosons, Mesons and Baryons** and each family may include a dozen or more fundamental particles many of which have corresponding **anti-particles**. Examples are **Muons, Gluons, Pions, Kaons** and the whimsically named **Up, Down, Top, Bottom, Strange and Charm Quarks** to name but a few. While this is interesting, nobody has yet found practical applications for these particles, but then **Rutherford** did not foresee any use for nuclear energy when he discovered nuclear radiation.

1932 G.W. **Heise** and W.A. **Schumacher** construct the first **zinc air battery**. High energy density primary cells, they were used to power Russia's **Sputnik 1** in 1957.

1932 Sabine **Schlecht** and Hartmut **Ackermann** working in Germany invent the porous **sintered pole plate** which provides a larger effective electrode surface area and hence lower internal impedance and higher current capabilities bringing about major improvements to **Nicad** battery design.

1932 **Nyquist** proposes a method for determining the **stability of feedback control systems**. Known as the **Nyquist stability theorem** it was developed from the study of the behaviour of negative feedback amplifiers but it has universal applicability being applied to mechanical systems (position, speed, temperature, pressure controls) as well as electrical systems (voltage amplitude, frequency and phase controls) and even non physical models such as the national economy. It is used as a development tool to ensure stability of electronic control and protection circuits. See also **Closed Loop Control Systems** for an explanation.

1932 Fibreglass, like glass, has been "invented" many times over. The first glass fibres of the type that we know today as **fibreglass** were discovered by accident by Dale **Kleist** working at Corning Glass. While attempting to weld two glass blocks together to form an airtight seal, a jet of compressed air unexpectedly hit a stream of the molten glass and created a shower of glass fibres indicating an easy method to create fibreglass. Fibreglass insulation had been patented in 1836 by **Dubus-Bonnel**, produced in volume by **Player** in 1870, patented again by **Hammesfahr** in 1880 and re-invented by **Boys** in 1887, however Russel Games **Slayter** of Owens-Corning was granted a patent for "Fiberglas" in1938.
The term 'fibreglass' is often used imprecisely for the composite material **glass-reinforced plastic (GRP)**

A fibreglass mat is an essential component used to absorb and immobilise the acid electrolyte in **AGM Lead Acid batteries**. **Fibreglass composites** are also used extensively for high power cell and battery casings.

1933 The "**Dassler** patent" recognized the oxygen cycle and **recombination** as fundamental principles of the **sealed nickel-cadmium battery**.

Research into improved nickel cadmium batteries by Schlecht, Ackermann and Dassler was driven by the need for light weight aircraft starting batteries.

1933 Walter **Meissner** and Robert **Ochsenfeld** discovered that when a **superconducting material** is cooled below its critical temperature magnetic fields are excluded or repelled from the material. This phenomenon of repulsion was discovered by **Faraday** and is known as

diamagnetism. The low temperature effect is today often referred to as the "Meissner effect".

1933 The first **injection moulded polystyrene** articles produced.

1933 Reginald O. **Gibson** and Eric William **Fawcett**, ICI chemists produced **Polyethylene** a polymer of ethylene gas. Like many chemical developments it was discovered by accident, this time while reacting ethylene and benzaldehyde at high pressure. Now used extensively in the electrical industry as an **Insulator** ICI gave it the name **Polythene**.

1933 Radio pioneer **Armstrong** patented **Frequency Modulation (FM radio)** as a way of reducing interference on radio transmissions. Since most electrical noise produces amplitude variations in the signal, Armstrong's system involved varying the frequency of the radio carrier wave (rather than the amplitude as in AM radio) in synchronism with the amplitude of the voice signal. By clipping the noisy signal the noise can be eliminated. The idea which revolutionised radio reception was at first rejected then stolen by his old friend David **Sarnoff** the founder and CEO of RCA in which Armstrong was a major shareholder.
Armstrong had previously fought a legal battle all the way to the supreme court over his 1912 invention of the **regenerative radio receiver** which amplified weak radio signals by feeding them back through a triode amplifier valve (tube). However in 1920 when the value of Armstrong's invention became known, Lee **De Forest** claimed ownership of the regeneration principle because it used his **audion**. Unfortunately after 12 years of litigation, the supreme court, not familiar at that time with such technical distinctions, found in De Forest's favour.
Like **Farnsworth** before him, Armstrong suffered at the hands of RCA. Short of funds and faced with more years of costly and heartbreaking litigation against former friends over his FM patents, in January 1954 Armstrong put on his hat, his overcoat and his gloves, stepped onto the ledge of his 13th floor apartment building in New York City and plunged to his death. His wife who had contributed to Armstrong's depression by refusing to help fund his litigation against RCA, continued it herself and eventually won.

1933 US patent awarded for **flexible printed circuits** made by Erwin E. **Franz** by screen-printing or stenciling a paste loaded with carbon filler onto cellophane, followed by a copper electroplating step to reduce the resistance. He also proposed using flexible folding circuits for windings in transformers.

1934 Lead acid batteries with **gelled sealed cells** were first manufactured by Elektrotechnische Fabrik **Sonneberg** in Germany.

1934 Invention of the transformer-clamp by **Chauvin Arnoux**, the very first **current measuring clamp**.

1935 The first practical **Radar** (**RA**dio **D**etection **A**nd **R**anging) system was produced by the Scottish physicist Robert Alexander **Watson-Watt** a direct descendent of James Watt the pioneer of the steam engine. As fears of an impending war grew, he had been tasked by the Air Ministry to come up with a radio death ray to disable enemy aircraft, however he informed them it was not possible and proposed instead the system we now call Radar for detecting the presence of aircraft before they came into sight. This was accomplished by sending out powerful radio pulses and detecting their return after reflection by the aircraft and computing the distance from the time it took the pulses to return. Large **directional antennas** were used to concentrate the signals and provide an indication of the bearing of the target. Being a two way system, one of the major

problems he had to overcome was to get very sensitive receivers to work in close proximity to very high power transmitters without being swamped. Watson-Watt received a knighthood in recognition of his achievements.
Ironically, after the war, Watson-Watt was amongst the first unsuspecting drivers to be caught in a Radar speed trap.

1935 German physicist Oscar Ernst **Heil**, working at Berlin University was granted a British patent for "Improvements in or relating to electrical amplifiers and other control arrangements and devices". His design was essentially an **insulated gate field effect transistor (IGFET)**. Using semiconducting materials such as Tellurium, Iodine, Cuprous oxide or Vanadium pentoxide to form a resistor between two terminals, he applied a voltage across the device. By means of a third control terminal he created an electrostatic field across the device at right angles to the current and by varying the voltage on this control terminal he was able to vary the resistance of the semiconductor and thus modulate the current through an external circuit.

Heil's transistor was never developed into a practical product. Semiconducting materials of sufficient purity were not available at the time and in the period leading up to and during World War II the scientific communities of whomever he happened to be working for had other priorities.

Heil however had other interests which benefited from the new focus on research applicable to military applications. He had married Agnessa **Arsenjeva** a Russian physicist while working in Russia. In 1935, the same year that he was granted the patent for his semiconductor amplifying device, together with his wife he published in *Zeitschrift fur Physik*, a paper on velocity modulation of electron beams entitled: "A New Method for Producing Short, Undamped Electromagnetic Waves of High Intensity" which outlined the fundamental working principles of the **klystron** tube, a high power microwave oscillator, used to provide the transmitter power in the newly developed radar equipment. Leaving Arsenjeva in Russia, he later moved to the UK to continue development work on the klystron with Standard Telephones and Cables (STC), the UK arm of ITT. The day before England went to war with Germany Heil slipped out of the country returning to Germany to continue his work at Standard Electric Lorentz (SEL), ITT's German arm in Berlin. Heil's klystrons, known as "Heil's Generators", became key components in Germany's World War II radars.

After the war Heil's name appeared on an FBI list of Germans accused of war crimes. He was brought to the US by the military and worked at Wright Patterson Air Force Base. Subsequently he formed his own company and carried out intensive research the physiology of the human ear and sound generation by small animals which he applied to the design of **sound transducers**. His 1973 patent for the **Heil Air Motion Transformer (AMT)** made him well known to HiFi buffs.

1930's Introduction of **Ampoule batteries** for use as military fuses.

1936 Carlton **Ellis** of DuPont was awarded a patent for **polyester resin** which can be combined with **fibreglass** to produce a **composite**.
The curing and manufacturing processes for polyester resin were further improved and refined by the Germans process. During World War II British intelligence agents stole secrets for the resin processes from Germany and turned them over to American firms. American Cyanamid produced the direct forerunner of today's polyester resin in 1942.

1937 The birth of **digital technology**. American mathematician Claude Elwood **Shannon** was the one of the first to realise the similarity between

electric switching circuits, **Boolean logic** and **binary arithmetic** and the first to use these principles as a basis for information processing in his MIT thesis on Vannevar **Bush**'s differential analyser. See also **Zuse** who developed these ideas independently. Shannon's work on digital technology formed a vital strand to his later work on **Information theory**.

Shannon, like Zuse, showed that **logic devices** which are commonly called **gates** may be implemented with mechanical switches, relays or valves (now transistors).
A computer can perform almost any logic or arithmetic operation using combinations of only three types of gates, called AND, OR, and NOT gates. If an "input" or an "output" is defined as a logic "1" and the absence of an input or output as a logic "0" then:

- **AND** gates give an output only if all the inputs to the gate are present.
- **OR** gates give an output if any of the inputs to the gate are present.
- **NOT** gates give an output if no input to the gate is present. A gate used for this function is also called an **inverter**.

1937 Eccentric English engineer and visionary Alec Harley **Reeves** working at ITT in France invented **pulse code modulation (PCM)** to minimise the effect of noise on transmission systems. Although his system was used for top secret communications during World War II, it needed many more components than conventional analogue circuits and it was not until the availability of integrated circuits that the large scale deployment of digital PCM systems became economically viable.

Electrical noise can be a serious problem with all **communications** circuits. As a signal progresses down a communications channel it gets weaker and at the same time picks up electrical noise. Each time the signal is amplified to restore its level, the noise is amplified with the signal until the signal may eventually be swamped by the noise. **Digital circuits** avoid this problem by using a transmitter which **samples** the analogue signal at high speed (See **Shannon** above) and converts the amplitude of the signal into a series of pulses, coded so that the pattern of the pulses represents the amplitude of the signal. This process is known as **quantising** and may be used to derive a simple binary number or some more complex encrypted data code. Noise affects the pulsed or digital signal in exactly the same way distorting the signal, however weak signals are not amplified to restore the signal strength. Instead, using a technique first employed by **Henry** in 1831, the distorted or noisy pulses are simply used to trigger a new set of clean, high level pulses to replace the weak and dirty signal pulses. The original pulsed waveform is thus **regenerated** and the noise is left behind. At the receiving end the original analogue signal is reconstituted from the pulses. Because of their noise immunity and amenability to multiplexing and computer controlled data manipulation, digital circuits based on Reeves' work have now almost completely replaced analogue circuits even for the simplest of functions. Standard integrated circuits are available to carry out the analogue to digital (A to D) and digital to analogue (D to A) conversions.

Although a pacifist, Reeves developed a pinpoint bombing system during the war "to minimise civilian casualties". He worked on radar systems, multipexers, fibre optics and acoustic components and was awarded over 100 patents. He also experimented with the paranormal using Geiger counters, pendulums, and electronics in his research and believed he was in regular contact with the long dead Michael Faraday. He claimed to have played in the French Open tennis championships - which were indeed 'open' to anyone who wished to participate. Reeves dedicated his private life to community projects, helping others, encouraging youth and rehabilitating prisoners.

1937 English engineer Robert J. **Dippy** working in **Watson-Watt**'s radar team conceived the **radio navigation** system using coordinated transmissions from three or more radio stations to pinpoint the location of a receiver. It relies on the fact that all the points where the time difference between radio signals from two different stations is constant form a hyperbola. The distance of the receiver from the transmitters (the locus of the hyperbola) can be calculated from the time differences from each transmitter. Signals from a second pair of stations determine another set of hyperbolas. The exact position of the receiver is determined by finding the point on the map where the two hyperbolas intersect. Dippy received a patent in 1942 for this invention which was implemented in the **Gee** navigation system used by the British Bomber Command in World War II. Dippy's principle of using intersecting radio beams was subsequently used in the **LORAN** navigation network and is used in the modern **GPS (Global Positioning by Satellite)** system in which the transmitters are located in orbiting satellites rather than in fixed ground based stations. Like computers, the early navigation systems were large and heavy and housed in equipment racks. Modern navigation receivers are hand held and battery powered.
After working as advisor on the development of LORAN in the USA, Dippy became a Divisional head of research in Australia's Defense Science and Technology Organisation.

1937 Printed circuits were demonstrated by London born British engineer with Hungarian parents John Adolphe **Szabadi**. In 1938 Szabadi changed his name to John **Sargrove** by which he is better known since Adolphe wasn't the most popular name in Britain at the time. His circuits were more like **thick film integrated circuits** than the **printed circuit boards (PCBs)** we know today. The system did not use etching as with modern PCBs. Instead, with the Sargrove method was an additive, process in which, not just the interconnecting circuit tracks but also the resistors, inductors, capacitors and other components were formed by spraying on to a pre-moulded bakelite panel.

1938 American engineer Hendrick Wade **Bode** building on **Nyquist**'s work at Bell Labs employs magnitude and phase frequency response plots of a complex function to analyse **closed-loop stability** in electronic systems. This formed the basis of **classical control theory** used in the design of stable electronic and other control systems.

1938 Canadian inventor Al **Gross** invented the **Walkiie-Talkie** two way mobile radio which was quickly picked up by the military and widely used during the war. In 1948, he pioneered **Citizens' Band (CB) radio** and in 1949, he invented the telephone **pager**.

1938 Chemist Otto **Hahn** and physicist Fritz **Strassman** from Germany and Lise **Meitner** from Austria verified the possibility of releasing energy by the phenomenon of **nuclear fission**, the **splitting of the atom**, first demonstrated by **Rutherford** in 1917. They bombarded uranium with neutrons and the uranium nucleus split into two roughly equal halves forming Barium and Krypton with the emission of three neutrons and a large amount of energy, the basis for the chain reaction which gave rise to nuclear power and bombs. From her work in Germany, Meitner knew the nucleus of uranium-235 splits into two lighter nuclei when bombarded by a neutron and that the sum of the masses the particles derived from fission is not equal to the mass of the original nucleus. She speculated that release of energy would be a hundred million times greater than normally released in the chemical reaction between two atoms. She was however not present when Hahn and Strassmann verified this result experimentally since, being Jewish, she was forced to flee to Sweden to escape Nazi persecution when Austria was annexed by the Germans. The results were published by Hahn and Strassmann and Hahn alone was eventually awarded a Nobel Prize for chemistry for this work. Meitner was not credited in the report since Hahn feared the result would be rejected if it were known to be tainted by "Jewish science", - female Jewish science at that. The German nuclear weapons research programme during World War II was led by **Heisenberg** and neither Hahn, Strassmann nor Meitner were involved.

1938 Contrary to popular belief, non-stick **Teflon** was not a product of NASA's space program. It was discovered by accidentally in 1938 by DuPont chemist Dr. Roy J. **Plunkett** while investigating possible new refrigerants. His lab technician Jack **Rebok** found an apparently defective cylinder of tetrafluoroethylene gas. Although it was the same weight as full cylinders, no gas emerged when the valve was opened. Rebok suggested sawing it open to investigate and inside, Plunkett discovered that a frozen, compressed sample of tetrafluoroethylene gas had polymerised spontaneously into a white, waxy solid to form **poly tetrafluoroethylene (PTFE)**.
PTFE has a high melting point, is inert to virtually all chemicals and is considered the most slippery material in existence. Now used as extensively an insulator or separator in a wide variety of batteries an other electrical equipment, it remained a military secret until after the end of World War II. Another secret? - How do they get Teflon to stick to the cookware?

1938 65% of British homes wired for electricity.

1938 German born American engineer Joseph G. **Sola** invented the **Constant Voltage Transformer (CVT)**. Based on ferroresonant principles it has a capacitor connected across the secondary winding. The voltage on the secondary winding increases as the input voltage increases, however the corresponding increasing flux produces an increase in the leakage reactance of the secondary winding and this approaches a value which resonates with the capacitor connected across it. This causes an increased current which saturates the magnetic circuit thus limiting any further rises in output voltage due to increased input voltage. The output may not be a pure sine wave but usable outputs can be obtained with a swing of +/- 25% in the input voltage. Furthermore, the transformer will absorb short duration spikes and due to the energy storage in the resonant circuit the output will hold up for short power interruptions of half a cycle (10 milliseconds) or more, making it useful for **UPS** applications.

1938 Swiss born German physicist Walter H. **Schottky** explained the rectifying behaviour of a metal-semiconductor contact as dependent on a barrier layer at the surface of contact between the two materials which led to the development of practical **Schottky diodes**. He had been one of the first to point out the existence of electron "holes" in the valence-band structure of semiconductors.

During his lifetime Schottky contributed many theories, designs and inventions including the **superheterodyne radio**, the **tetrode valve** and the **ribbon microphone** which transformed the electronics industry.

1938 German civil engineer Konrad **Zuse** completed the world's first **programmable digital computer**, an electromechanical machine, which he called the **Z1**. Started in 1936, it was built in his parents' apartment and financed completely from his own private funds. It pioneered the use of **binary arithmetic** and contained almost all of the functions of a modern computer including control unit, memory, micro sequences and floating point arithmetic. Programs were input using holes punched into discarded 35-millimetre movie film rather than paper tape and data was input through a simple four decimal place keyboard. The calculation results were displayed on a panel of light-bulbs. The clock frequency was around one Hertz. Relays can be used to store data since the position of the contacts, closed or open, can be used to represent a one or a zero, but Zuse did not use this solution because relays were very expensive. Instead he devised a **mechanical memory system** for storing 16 X 22-bit binary numbers in which each memory cell could be addressed by the punched tape or film. For storing data it used small pins which could slide in slots in movable steel plates mounted between sheets of glass which held them together. The pins could move and connect the the plates and their position at either end of the slot was used to store the value 0 or 1. Individual memory units could be stacked on top of one another in a system of layers. In keeping with the German tradition of solid engineering Zuse claimed "These machines had the advantage of being made almost entirely of steel, which made them suitable for mass production".

Zuse was called up for military service in 1939 but was later released from active service, not to work on computers as might be expected, but to work as an aircraft engineer. He continued the development of his ideas in his spare time and, despite the shortages of materials, in 1941 he demonstrated his third machine imaginatively called the **Z3**. With limited backing from the DVL, the German Aeronautical Research Institute, this time he was able to use 2,600 relays, which were more reliable than his metal plates, to form the memory **registers** and the **arithmetic unit**. The memory capacity was increased to 64 words and the clock frequency was increased to 5.33 Hertz. The Z3 is the undisputed, first fully programmable practical working electronic digital computer. It was programmed using punched tape but because of size limitations of the memory, the Z3 did not store the program in the memory. Otherwise it used the basic **architecture**, patented by Zuse in 1936, and all the components of a modern computer, the concept for which Hungarian born American mathematician John **von Neumann** was later credited for defining in 1946.

After the success of the Z3 the government at last took notice of Zuse's work but when in 1942 he proposed a computer based on much faster electronic valves, it was rejected on the grounds that the Germans were so close to winning the War that further research effort would take too long and was therefore not necessary.

In the early aftermath of the war West Germany was prohibited from developing electronic equipment, materials were even scarcer than before and electrical power was only available intermittently. His latest computer the **Z4** had also been damaged in the Berlin air raids but Zuse had managed to rescue it and after many difficulties he was eventually able to restart its development in Switzerland. Completed in 1950, the Z4 was the first computer in the world to be sold to a commercial customer, beating the Ferranti Mark I in the UK by five months and the UNIVAC I in the USA by ten months.

Between 1942 and 1946 Zuse also developed **Plankalkül** (German, "Plan Calculus") the world's first **high level programming language** but did not publish at the time. It included assignment statements, subroutines, conditional statements, iteration, floating point arithmetic, arrays, hierarchical record structures, assertions, exception handling, and other advanced features such as goal-directed execution. Intended as an engineering tool for performing calculations on structures, Zuse also used Plankalkül to write a program for playing chess. At that time the concept of **software** was unheard and surprisingly he did not start with machine oriented **assembly language programming** but immediately set out to develop the more complex user oriented language. Plankalkül was the first modern programming language at any level above manual toggle switching or raw **machine code**. It was finally published in 1972 and the first compiler for it was implemented in 2000 by the Free University of Berlin, five years after Zuse's death.

Until 1950 Zuse lived in complete isolation from the world outside Germany particularly during the war years when he remained in Berlin where his first three computers and his workshop were destroyed by allied bombing raids. He had little knowledge of computer developments elsewhere and his work was likewise almost unknown outside of Germany, although IBM obtained an option on his patents in 1946. He was not successful as a businessman and his company was sold to Siemens in 1967. Besides his engineering talents Zuse was also an accomplished artist who sold his paintings during his early years to fund his studies and at the end of the war sold woodcuts to American troops in order to buy food. In retirement he returned to painting as a hobby.

There have been many claimants to the title of **The First Computer**. For the record here are the dates when some other early programmable computers became fully operational:

- 1941 **Zuse Z3** (Germany) See above.
- 1942 **ABC** (Unfinished) (USA) The **A**tanasoff-**B**erry **C**omputer, built by John Vincent **Atanasoff** and his graduate student Clifford **Berry** at Iowa State University. It used 311 vacuum tubes (valves) to perform binary arithmetic but it was not a stored program machine nor was it fully programmable but program changes could be input using switches. It was abandoned before it was completed when Atanasoff left to do military service. At the time, neither Atanasoff nor the Iowa University thought it necessary to patent any of the innovative concepts used in the ABC.
- 1943 **Colossus** (UK) Built by Post Office engineer Thomas (Tommy) Harold **Flowers**, and mathematicians Maxwell (Max) Herman Alexander **Newman** and Alan Mathison **Turing** at Bletchley Park. The first all-electronic calculating machine, used during WWII to break German codes. Turing's role was in developing the code breaking procedures and he was not involved in the design of the machine which was done by Flowers. Colossus used 1,500 vacuum tubes to perform boolean operations. The machine was programmed using switches and cables in a patch panel which needed rewiring to implement program changes. Data was entered using punched tape. Ten Colossi were built and used in great secrecy and no attempt was ever made to commercialise them. At the end of the war **Winston Churchill** ordered eight of them to be smashed "into pieces no bigger than a man's hand" and all the drawings to be burned. The two remaining machines were sent to GCHG the UK government's top secret communications centre. It was not until 1970 that existence of the Colossus was revealed publicly as the result of the USA's Freedom of Information Act. (The US government had been given details of Colossus during the war as part payment for US assistance to the UK's war effort.)
- 1944 **Harvard Mark 1** (AKA **IBM ASCC**) (USA) Built by IBM's Howard **Aiken**. An automatic digital sequence-controlled computer, based on relays and rotary switches. It used decimal arithmetic and programs were entered using punched tape.
- 1946 **ENIAC** (USA) Electrical Numerical Integrator and Calculator, built by John Presper **Eckert** and his student John W. **Mauchly** at the University of Pennsylvania. It used 18,000 vacuum tubes and consumed almost 200 kilowatts of electrical power. It was a single purpose machine designed to plot missile trajectories. Calculations used decimal rather than binary arithmetic and it was not a stored program machine. Programs were entered manually using switches and cable connections in an external patch board and were modified by rewiring. The forerunner of the UNIVAC (Universal Automatic Computer) machine launched by Remington Rand in 1951 after they had purchased Eckert and Mauchly's company, the ENIAC used design concepts Mauchly had copied from Atanasoff's ABC machine for which Atanasoff

received neither credit nor recognition. In 1973 when Sperry Rand tried to extract royalties for the use of its ENIAC computer patent they were challenged in court by Honeywell and the court voided Sperry Rand's patent declaring it to be a derivative of Atanasoff's inventions.

- 1948 **Manchester Mark 1** (AKA **"Baby"**) (UK) Built by Max H.A. **Newman** and Freddie C. **Williams** with software written by Tom **Kilburn**. The first computer with a true stored-program capability and von Neumann architecture, it used the persistence of the image on the phosphor screen of a cathode ray tube (CRT) for data storage and binary arithmetic for processing. The Manchester Baby was the basis for the **Ferranti Mark 1** introduced in 1951, one of the first commercially available computers.
- 1949 **EDSAC** (UK) Electronic Delay Storage Automatic Computer, built by Maurice V. **Wilkes** at Cambridge. A true general purpose stored program machine using binary arithmetic. Not to be confused with Eckert and Mauchly's **EDVAC** Electronic Discrete Variable Automatic Computer which did not become fully operational until 1952, it was the first to use a **mercury acoustic delay line** for data storage.
- 1949 **LEO** (UK) Lyons Electronic Office, the first business computer, derived from EDSAC and developed by **J.Lyons and Company**, a British catering firm.

Echoing **Babbage**'s experience, with four out of the first eight modern computers, UK innovation once more was not translated into commercial success.

Computers have become essential tools in almost every aspect of engineering and business management and their modern counterparts, microprocessors are now key components in battery management systems.

1939 The German company I.G. Farbenindustrie filed a patent for polyepoxide (**epoxy**). Benefiting from German technology **epoxy resins** were made available to the consumer market almost four years later by an American manufacturer. They have very strong adhesive properties being one of the few materials which can make effective joints with metal. They are dimensionally stable and have similar expansion rates to metals. When combined with fibreglass they can produce an extremely strong composite materials, known as **Glass Reinforced Epoxy (GRE)** , strong enough for use as aircraft components.
Because of epoxy's chemical resistance and excellent electrical insulation properties, electrical parts such as batteries, relays, coils, and transformers are insulated with epoxy.
See also **polyester resins**.

1939 Almost two thirds of British households have electric lighting.

1940 John Turton **Randall** and Henry Albert Howard **Boot** working at Birmingham University developed the first practical **cavity magnetron**, a high power microwave transmitter valve (vacuum tube) which was an essential component in wartime Radar transmitters. It could generate 1000 times the power of any other existing microwave generator at the time. Now an essential component in **microwave ovens**.

1941 Silver oxide- Zinc (Mercury free) primary cells developed by French professor Henri **André** using cellophane as a semi permeable membrane separator which impeded the formation of dendrites which caused short circuits.

1941 Bell Labs researcher Russell S. **Ohl** discovered that **semiconductors** could be **"doped"** with small amounts of foreign atoms to create interesting new properties. He discovered the principles of the **P-N junction** (with some hints from Walter **Brattain**) and invented the first Silicon **solar cell**, a P-N junction that produced 0.5 volts when exposed to light. Ohl's invention of the semiconductor junction and his explanation of its working principles laid the foundations on which the invention of the **transistor** was based. Unfortunately, Ohl's essential contribution has almost been forgotten.

1941 American inventor B.N. **Adams** filed for a patent on the **water activated battery**. Working at home, he had developed the battery for military, marine and emergency us and he demonstrated it to the US Army and Navy. Unfortunately the US Army Signal Corps declared the invention to be unworkable. Nevertheless Adams was awarded a patent in 1943. At the height of World War II however the US Signal Corps decided the idea was indeed feasible after all and the government entered into procurement contracts with several battery making companies without informing Adams. He subsequently discovered in 1955 that his invention had been in use for some time by the US government who by then claimed the idea lacked novelty and was obvious and was therefore not patentable. In 1966 Adams sued the US government and the Supreme Court found in his favour and his 1943 patent was upheld.

1941 Patent granted to American inventor Harold **Ransburg** for the **electrostatic spray coating** process in which the paint is electrostatically charged and the surface to be painted is grounded. An idea first proposed by **Nollet** in 1750. Because of the electrostatic attraction between the positively charged paint and the grounded body the majority of the paint reaches its target resulting in major savings.

1941 Thick Film Circuits developed by Centralab division of Globe-Union Inc in the USA - An innovative use of **screen printing technology** patented in 1907. They used resistive inks and silver paste printed on ceramic substrates to form printed resistors, capacitors, links and other components in miniature circuits used in proximity fuses. Similar printing processes are used today to manufacture **thin film batteries**.

1942 Building on **Chadwick**'s work, the first controlled, self-sustaining **nuclear chain reaction** was achieved by a team led by Italian **Enrico Fermi** in an **atomic pile** set up in a squash court at the University of Chicago. During **nuclear fission**, a fast-moving neutron splits an atom's nucleus, which results in the release of energy and additional neutrons. These ejected neutrons can split further nuclei, which release more neutrons to split yet more nuclei, and so on creating a self-sustaining chain reaction. If this chain reaction goes too fast, it becomes an **atomic explosion**, but under control it could produce a steady flow of energy. If the chain reaction starts with uranium, it also creates a byproduct, plutonium, a better fuel for a nuclear weapons. Fermi found that cadmium would absorb neutrons. If the chain reaction speeded up, cadmium rods could be inserted into the pile to slow the reaction down and could be removed to accelerate it again. If the cadmium control rods had failed or if they had got their calculations wrong, half of Chicago would have been blown up. As a precaution physicist Norman **Hilberry** stood poised with an axe during the start-up, ready to cut a rope and release more cadmium control rods that would stop the reaction in an emergency. If all else failed, a three-man "suicide squad" of physicists stood ready to drench the pile with cadmium sulfate.
This event marked the birth of the **nuclear power** industry and also the **atom bomb**.

1942 American chemist Harry **Coover** working on materials for optically clear gun sights accidentally discovered **cyanoacrylate** a fast acting transparent adhesive. It proved too sticky for the job in hand and its true potential was not realised until 1958 when it was marketed as **Superglue**. Now used extensively in industry for glueing together small sub-assemblies such as battery packs.

Superglue's ability to stick skin together was turned from a problem into a benefit during the Vietnam War saving the lives of countless soldiers when it was used in to seal battlefield wounds before the injured could be transported to a hospital.

1942 American chemists William Edward **Hanford** and Donald Fletcher **Holmes** working at du Pont de Nemours invented the process for making the multipurpose material polyurethane. Now extensively used as a foam insulating material in a wide range of applications.

1943 The **printed circuit board** was patented in the UK by Austrian born Jewish refugee Paul **Eisler**, the acknowledged father and publiciser of the PCB. Most of Eisler's patents were for a subtractive process whereby circuit tracks were made by etching copper foil which has been bonded to an insulating substrate. Like the **plug**, this simple invention was late in arriving - only four years before the much more complex transistor. There had been many proposed designs for PCBs over the previous 40 years, using a wide range of different processes by **Hanson**, **Berry**, **Schoop**, **Ducas**, **Parolini**, **Seymour**, **Franz**, **Sargrove**, **Centralab** and others, but Eisler's processes were more practical and were quickly adopted by the US Army. Despite this, it was not until the 1950's that the use of PCBs finally took off, helped no doubt by the advent of the transistor.
Some of the processes involved in Eisler's patents were borrowed from the printing industry and some of the patents mentioned above were cited by Eisler in his patent applications and although the use of PCBs was virtually unknown at the time Eisler's patents were granted, they were challenged by the Bendix Corporation in the USA and overthrown in 1963 on the grounds of prior art. Eisler died in 1995 a bitter man.
Eisler held patents for a number of other popular developments, mostly involving heated films, including the rear windscreen heater, heated wallpaper, food warmers for fish fingers and other foods, heated clothes (John Logie **Baird** got there first with his 1918 patent for damp-proof socks) and also a battery powered pizza warmer for take out pizzas.

It was another six years before **dip soldering** was invented.

1944 Samuel **Ruben** an independent inventor in the USA developed the mercury **button cell** licensed to a company owned by Philip Rogers **Mallory**. The war years stimulated the development of new cell chemistries with **water activated batteries**, **silver oxide** and **mercuric oxide cells** after over forty years with few major advances.
The mercury cell is an aqueous system primary cell based on and zinc and mercuric oxide. They made a major impact at the time, replacing the poorer performing zinc carbon cells, providing high energy density and the ability to work in harsh environments. Millions were produced by Mallory for powering "Walkie Talkie" two way radios, amongst other things, as part of the war effort. With the invention of the transistor, mercury cells were eagerly adopted for powering hearing aids and transistor radios. Subsequently the use of mercury in batteries has been banned by many countries because of its toxicity and mercury cells have been replaced by other cell chemistries.

Ruben and Mallory went on to found the Duracell company.

1944 A. **Brenner** and G. E. **Riddel** discovered the possibility **Electroless Plating** or **Electroless Deposition** which they subsequently developed and patented in 1947. L. **Pessel** also applied for a patent for a method of plating non-metalic objects in 1944. Electroless plating uses a redox reaction to deposit metal on an object without the passage of an electric current. Because it allows a constant metal ion concentration to bathe all parts of the object, it deposits metal evenly along edges, inside holes, and over irregularly shaped objects which are difficult to plate evenly with electroplating. Electroless plating is also used to deposit a conductive surface on a nonconductive object to allow it to be electroplated. The chemical reduction process depends upon the catalytic reduction process of metallic ions in an aqueous solution containing the chemical reducing agent. The process needs a catalyst such as Platinum or Palladium to kick start it but once the process has started the catalytic action of the deposited metal is often enough to sustain the reaction. The process is extensively used to deposit metal coatings on plastic parts either for cosmetic purposes or to provide EMC shielding for electronic circuits contained within plastic housings. It is also used in the manufacture of PCBs.

1945 John R. **Ragazzini** at the University of Columbia demonstrated an **operational amplifier (op-amp)**, implemented with vacuum tubes, incorporating ideas from technical aid George A. **Philbrick**. An op-amp is a high gain DC amplifier with a voltage gain of 100 to 100,000 or more and a very high (ideally infinite) input impedance and very low (ideally zero) output impedance. They can not only add or subtract incoming signals but can also invert, average, integrate, and otherwise manipulate them, facilities which later made them the idea and indispensable building blocks of analogue electronic circuits.

1946 Felix **Bloch**, working at Stanford University, and Edward **Purcell**, from Harvard University, found that when certain nuclei were placed in a magnetic field they absorbed energy in the radio frequency range of the electromagnetic spectrum, and re-emitted this energy when the nuclei transferred to their original state. The strength of the magnetic field and the radio frequency matched each other, that is, the angular frequency of precession of the nuclear spins is proportional to the strength of the magnetic field. This relationship had been earlier demonstrated by Sir Joseph **Larmor** (Irish physicist 1857-1942) and is known as the Larmor relationship. This phenomenon of absorption and re-emission of energy was termed **Nuclear Magnetic Resonance (NMR)** and the technology later formed the basis of **MRI scanners**. They were awarded the Nobel Prize in physics in 1952 for their discovery.

1946 Working on Radar projects with the Raytheon company, self taught engineer Percy Le Baron **Spencer** was testing a **magnetron** when he discovered that a candy bar in his pocket (so he said) had melted. Realising that the microwaves he was working with had caused it to melt, he experimented with popcorn and eggs and discovered that microwaves would cook foods more quickly than conventional ovens. By late 1946, the Raytheon Company had filed a patent for the idea and set about designing a commercial **microwave oven** which was eventually launched in 1947. It sold for $5000 and was the size of a large refrigerator standing 165cm (5 1/2 feet) tall and weighing over 340 Kg (750 pounds). The magnetron had to be water-cooled, so plumbing installations were also required. It was another 20 years before the size and costs were reduced enough for the product to achieve commercial success.

1946 Ceramic magnets developed by **Philips** during World War II are introduced. Consisting of a mixture of oxides of iron and other metals these **magnetic ferrites** revolutionised the design of inductors, transformers, motors, loudspeakers and high power vacuum tubes.

1947 The **transistor** invented by Americans John **Bardeen**, Walter Houser **Brattain** (born in China) and William Bradford **Shockley** working at

Bell labs in the USA. This invention marked the birth of the massive semiconductor industry. Because of their enormous investment in telephone plant, the Bell System was one of the last companies to use their own invention.
The trio were awarded the Nobel Prize for physics in 1956 for their work.

The reality behind workings of this famous group was a little different from that portrayed by the Bell Labs PR machine.
The pioneering work on the transistor was in fact done by close friends Bardeen, the theorist, and Brattain, the experimenter, two talented though modest researchers. Shockley was their brilliant but arrogant supervisor, a direct descendent of pilgrims who came to America on the Mayflower. He had paid little attention to their work until they made their breakthrough, whereupon, with the encouragement of Bell Labs management, he suddenly became deeply involved, especially when the credit was to be shared out. Bardeen and Brattain were actually awarded the patent for the **point contact transistor** **(diagram)** which they first demonstrated in December 1947. Built by Brattain it was made from a ribbon of gold foil around a plastic former in the shape of a triangle. At one of the points he sliced through the ribbon with a razor blade to make two connections, the emitter and the collector, spaced very closely together. This point of the triangle was placed gently down on to a base block of **Germanium** to which was made the third connection. By varying the voltage on the base, the current between the two other connectors could be controlled. Turning this lab model, which had all the frailties and variability of the cat's whisker, into a practical device was difficult however and point contact transistors were never widely used. One of the main obstacles to overcome was the need for very thin base layers, (of the order of 1 micron or less), to obtain low capacitance and high frequency range and at the same time to to make reliable connections to this layer. Transistors went through many design iterations and 10 years of development before settling on the **planar** structure.

Building on their work, Shockley first proposed a design for a **field effect transistor** but it fell foul of **Lilienfeld**'s 1930 patent. Then working feverishly through January 1948 by the end of the month Shockley devised the **junction transistor**, a single semiconductor sandwich with three layers, which was easier to manufacture, more stable and could handle more power than the fragile point contact transistor and he was also awarded a patent for this new device. It was another two years however before the development of **Teal**'s manufacturing techniques for growing single crystals made it possible to turn Shockley's vision into a reality.
Relations between the abrasive Shockley and his two researchers subsequently deteriorated beyond breaking point and Bardeen and Brattain both left Bell Labs. **Bardeen** went on to gain a second Nobel prize in 1972 for his work on **superconductivity**.

One key contributor, sadly overlooked in the credit shareout for this breakthrough technology, was fellow Bell researcher Russell **Ohl** who developed the technology of the P-N junction which made the transistor possible.

Shockley himself left Bell Labs 1955 to form his own semiconductor company, the first in Silicon Valley. Because of his technical reputation he initially attracted the most talented young men in the industry but within a year his egotistical management style drove them out. A group of these short term alumni known as the **Traitorous Eight** left en masse in 1957 to found the Fairchild Semiconductor company. Between them they created the foundations of the world's semiconductor industry. They included Swiss physicist Jean **Hoerni**, inventor of the planar process which made integrated circuits possible and Gordon **Moore** and Robert **Noyce** who went on together to found Intel in 1968. In 1962, along with Jay **Last** and Sheldon **Roberts**, two other members of the Traitorous eight, Hoerni founded Amelco now known now as Teledyne. Then in 1964, Hoerni

founded Union Carbide Electronics and in 1967 he founded Intersil. Shockley shared none of the wealth of his alumni and his company eventually folded. At the same time he became an outspoken proponent of eugenics and the notion that intelligence was genetically determined by race which tarnished his reputation and led to his eventual disgrace. Alexander Graham **Bell** had also been an advocate of eugenics but was more circumspect in his views and did not attract the opprobrium provoked by Shockley.
Fairchild was the breeding ground of many more semiconductor pioneers, known as the **Fairchildren**, who went on to found their own companies. Amongst these were Fairchild's top salesman the flamboyant Jerry **Sanders** who left to found AMD and Hungarian born Andrew S. **Grove**, Assistant Research and Development Director, who left to found Intel with Moore and Noyce.

1947 Bell Laboratories introduced the concept of **cellular communications** but the computer and switching technologies needed to make it work did not yet exist. (See 1973 Martin **Cooper**)

1947 Neumann (France) Develops successful **seal** for the **nickel-cadmium battery** making possible a practical **recombinant system** in which the gases generated by the chemical reactions are recombined, rather than vented to the atmosphere, to prevent loss of electrolyte. This recombinant system, together with the benefits of low weight and volume, led to their widespread adoption of NiCads for portable applications bringing about a gradual renaissance in the use of DC power for domestic products and creating the demand for cordless appliances (later expanded and satisfied by other cell technologies).

1947 First commercial application of a **piezoelectric** ceramic, barium titanate used as a **gramophone needle**.

1947 The **hologram** patented in the UK by Hungarian born refugee from Germany, Dennis **Gabor**. Reflection and transmission types are possible. They use a coherent light source (now provided by a laser beam) which passes through a semi reflecting plate which acts as a beam splitter to create a reference and an object beam. Light from the object beam is reflected off the object and is projected onto a photographic plate. Light from reference beam reflects off a mirror and also illuminates the photographic plate. The two beams beams meeting at the photographic plate create an interference pattern representing the amplitude and phase of the resultant wave which is recorded on the plate. The 3D holographic image is reconstructed by reversing the procedure. Holograms are easy to read but difficult to copy. They can be printed on labels and are used in the battery industry to provide a method of **secure product identification**.
Gabor received over 100 patents and was awarded the Nobel Prize for Physics in 1971.

1947 American manufacturing engineer John T. **Parsons** linked an IBM accounting computer with its **punched card system** to a milling machine and created the first **numerically controlled machine** for cutting two dimensional curves. He expanded on the idea in 1948 producing a three axis controller capable the cutting of three dimensional components.
Amazingly it took over 140 years before someone applied the automation techniques, used by **Jacquard** and others in the 18th century weaving industry, to metal machining.

1948 After a period of secrecy the **transistor** was announced to the press on July 1. The start of a revolution in electronics was reported by "New York Times" in 4½ column inches at the end of its radio chat section on page 46.

1948 German physicists Herbert F. **Mataré** and Heinrich **Welker** working at Westinghouse in Paris applied for a patent on an amplifier which they called the **transistron**, the so called **French transistor**. It was a point contact device based on the semiconductor minority carrier injection effect which they had discovered independently of Bell Labs. Mataré had first observed transconductance effects while working on germanium duodiodes for German radar equipment during World War II. Westinghouse however concluded that there was no market for the transistron and closed their Paris lab to concentrate their resources on nuclear power engineering. Mataré returned to Germany in 1952 to found the transistor company Intermetall and Welker went to work for Siemens.

1948 Americans Gordon K. **Teal** and John B. **Little** from Bell Labs used the Czochralski (CZ) method to grow **single crystals** of Germanium, which began its use as a fundamental process in the manufacturing of semiconductors. The growing of large quantities of monocrystalline semiconductors by pulling the crystal from the melt was an absolute necessity for the production of high volume low cost transistors.

Despite lack of support (or even opposition) from Bell management, Teal persevered with the development of crystal growth technology and working with fellow physical chemist Morgan **Sparks**, he adapted the Czochralski method to allow doping of the crystals as they were pulled from the melt. Known as the **grown junction technique**, P and N type impurities were successively added in turn to the molten Germanium to build up the three layer NPN or PNP sandwich. The slice, or **wafer**, containing the layers was then cut from the crystal and then cut up again into smaller sections the desired size of the transistor. Wires were then attached to each layer and the device was encapsulated. Using this technique, in 1950 Teal successfully fabricated the first working **junction transistor** from a Germanium crystal two years after it had been proposed by **Shockley**. The frequency response of early junction transistors was unfortunately inferior to that of point-contact devices because it was difficult to grow a thin enough base region and then to attach leads to it once it was grown. For this and for commercial reasons Bell Labs held off announcing this achievement until 1951, one month after GE's announcement of the alloy junction transistor. Nevertheless the grown junction transistor became the first semiconductor device with enough predictability and dependability to be used in high volume consumer goods.

Also in early 1951 Teal, working with technician Ernest **Buehler**, grew the first **single crystals of silicon** and doped them with impurities to make **solid-state diodes** once more publishing the results a year later.

In 1952 Teal moved to Texas Instruments (TI) where he pioneered the use of Silicon rather than Germanium technology for semiconductor manufacturing.

1948 Shannon publishes "A Mathematical Theory of Communication", outlining what we now know as **Information Theory**, describing the measurement of information content of a message and the use of **binary digits** to represent yes-no alternatives - the fundamental basis of today's telecommunications.

Using Boltzmann's concept of **entropy** (a measure of uncertainty), Shannon demonstrated that decreases in uncertainty (or entropy) correspond to the information content in a message.

Shannon's equation for **information entropy** shows the same logarithmic relation that the Boltzmann equation for **thermodynamic entropy** does.

He used this measure of information to show how many extra bits would be needed to efficiently correct for errors when the message was transmitted on a noisy channel.

Shannon is also credited with the introduction of the **sampling theory** which governs how a continuous-time signal can be represented by a (uniform) discrete set of samples. The foundation of signal digitisation.

Shannon was surprisingly reclusive working alone at Bell Labs keeping his door shut. He had two hobbies which he often combined, juggling and designing with whimsical toys. His inventions included a two-seated unicycle, a unicycle with an off-centre hub, juggling machines, rocket-powered Frisbees, a motorised Pogo stick, mechanical maze-solving mice and a device that could solve the Rubik's Cube puzzle. He would emerge from his office at night to ride his unicycle down the halls while at the same time juggling three balls. In later life he was afflicted by Alzheimer's disease, and he spent his last few years in a nursing home.

1948 Patent granted to UK academic Eric **Laithwaite** for the **linear motor**. In 1965 Laithwaite outlined the principles of **magnetic levitation and propulsion** used in **maglev trains** in an IEE paper entitled "Electromagnetic Levitation". Unfortunately his ideas found little support from either the British government or British industry. In 1969 a US patent for a magnetic levitation train propelled by linear motors based on Laithwaite's ideas was granted to James R. **Powell** and Gordon T. **Danby** and since then several systems have been installed around the world.

1949 The patent for the **Bar code** system, using thick and thin lines inspired by Morse code, was filed in the USA by recently graduated students Norman J. **Woodland** and Bernard **Silver**. It was 1974 before the bar code system was first used in a retail store checkouts. Bar code labels are used in the battery industry to record manufacturing data such as product **identification**, date of manufacture and serial number to simplify inventory management and to facilitate traceability of suspect products.

1949 American engineer Jay Wright **Forrester** working at MIT, invented the **magnetic core random access memory (RAM)** replacing vacuum tubes (valves), whose state could be "On" or "Off", with tiny annular magnetic cores whose state could be "magnetised" or "not magnetised". His invention was actually preceded by a design by **Wang** working at Harvard, whose patent was not awarded until 1955.

1949 Dip soldering invented by Stanislaus (Stan) Francis **Danko** and Moe **Abramson** of US Army Signal Corps, six years after the invention of the **printed circuit board (PCB)**.

1950 Shockley published his classic text on transistors, **Electrons and Holes in Semiconductors**. Even into the 1950's the theory and structure of semiconductors was not well understood and it took experiments using cyclotron resonance to reveal the nature of electrons and holes in silicon and germanium.

1950 Shockley first described the idea for a **four layer PNPN transistor** which he referred to as a bipolar transistor with a P-N hook-collector. The mechanism for the operation of the device was analysed further in 1952 by Jewell James **Ebers** another Bell Labs physicist and in 1956 Bell Labs engineers John Louis **Moll**, Morris **Tanenbaum**, J. M. **Goldey**, and Nick **Holonyak**, Jr., published a paper outlining its use as a transistor switch.

The device was however first turned into a practical product, the **silicon controlled rectifier (SCR)** or **thyristor** (from the Greek "thyr" - door or gate) in 1956 by Gordon Hall at G.E.

Shockley on the other hand left Bell Labs in 1955 to pursue its application as a four layer diode, which he named after himself, in his own company Shockley Semiconductor Laboratory.

1950 Jun-ichi **Nishizawa** working at Tokyo University invented the PIN diode.

1950 The Swiss firm **Oerlikon** developed the so-called gyrobus, a flywheel powered electric bus first used in Yverdon, Switzerland in 1953. The flywheel battery incorporated an electric motor which was used to re-charge the flywheel at bus stops (**Opportunity charging**).

1950 as a result of work carried out in the 1940's, John **Dreyer** working at the Marconi Laboratories in England patented a method for orienting dye molecules in **liquid crystals** to make **polarisers**. See also Reinitzer (1888)

1950 American physicist and statistician W. Edwards **Deming** invited to Japan by Japanese business leaders to teach American methods of statistical analysis, quality control and process improvement. He stayed for many years and with the Japanese and others brought a completely different focus on the conception of quality - it was concerned with methods for improvement, striving to do better, not control and conformance. Building on Japanese working practices of constant improvement, teamwork, responsibilities and setting high standards he developed the concept of **Total Quality Management (TQM)**. The results were so spectacular that Deming was credited with being a major influence in the success of Japan's post war economic recovery and the Japanese were invited back to the West to explain their methods to western business leaders.

1950 The modern **gas-liquid chromatography** technique was invented by British chemist Archer John Porter **Martin**. Based on principles first proposed by Tswett, a sample of gaseous or liquid to be analysed is injected into a long tube together with a carrier gas or liquid which sweeps the samples through the tube. This motion of the sample molecules is inhibited by the adsorption either onto the tube walls or onto packing materials in the tube. The rate at which the molecules progress along the tube depends on how quickly they are absorbed and this in turn depends on both the type of molecule in the sample and on the absorbent materials. Since each type of molecule has a different rate of progression, the various components of the sample are separated as they progress along the tube and reach the end of the tube at different times. A detector monitors the outlet stream from the tube. The time for each component to reach the outlet is unique for the particular component in the sample allowing it to be identified. The amount of that component can also be determined. Generally, substances are identified by the order in which they emerge from the column and by the time required for the sample to pass through the tube. The gas-liquid chromatograph is a basic laboratory tool for analysing the chemical materials used in energy cell manufacturing.
Martin who had invented a series of chemical analysis machines over the years was awarded the Nobel Prize for chemistry in 1952.

1951 The first **computer programming** textbook published: "The Preparation of Programs for an Electronic Digital Computer" by Maurice V. **Wilkes**, David J. **Wheeler**, and Stanley **Gill**, the pioneering software team who developed **assembly language programming** for Cambridge University's EDSAC (Electronic Delay Storage Automatic Calculator) computer, which they completed in 1949. The book outlined assembly language programming, writing machine instructions in mnemonic form using **symbolic instruction code** and an assembler to convert the mnemonics into into binary **machine code** instructions which the computer could understand. It also introduced the notions of **reusable code** with **subroutines** and **libraries**. Assembly language was an essential step on the road to the high level programming languages we use today.

1951 Grace Murray **Hopper** of Remington Rand, invents the modern concept of the **compiler**. A compiler is a computer program which translates **source code** written in a high level language to **object code** or **machine language** that may be directly executed by a computer or microprocessor. It allows programs written in high level languages to be run on different machines.
As an example, the software used to run an **embedded system** such as that used in a **battery management systems (BMS)** will normally be developed off line on a PC or other general purpose computer using a high level language such as "C". This source code will then be compiled into machine code which will run on a dedicated microprocessor in the BMS. This object code is downloaded into, and stored in, the BMS memory and runs when the system is switched on or when it is called to do so by external inputs.

Grace Hopper worked with **Aiken on** the **Harvard Mark1** computer and with **Eckert** and **Mauchly** on the **ENIAC** and in the US navy she rose to the rank of Rear Admiral. In 1945 when she found a moth between the contacts of a relay in an early computer, causing a malfunction, she coined the word "bug" for a computer fault, and the word "debugging" when the insect was removed.

1951 American engineer John **Saby** working for GE made the first **alloy junction transistor** **(diagram)** one month before Bell's announcement of their **grown junction transistors**. In the alloy junction process two small pellets of P type impurities were placed on opposite side of a thin disc of N type Germanium and heated till the pellets melted into the Germanium fusing into alloyed regions within the Germanium base. The heating stopped short of melting right through the Germanium leaving a narrow N type base layer between the P type emitter and collector. Wires were then connected to the three regions.

At Philco young engineer Clare **Thornton** found a way to improve on the alloy transistor in 1953 by using a **jet etching technique** to create thinner more controllable base sections. The Germanium base was electro-chemically etched on opposite sides by a jet of chemical etchant with an electrical bias until the Germanium reached the desired thickness (translucent to visible light) when the etching was stopped. The emitter and collector pellets were placed in the depressions created and alloyed as normal **(diagram)**. This enabled them to produce transistors which could operate with reasonable gains beyond 30 MHz. Devices made this way were called **surface barrier transistors**.

1951 Automated Assembly introduced by **Ford Motor Company** for producing engines. Actually more than just assembly, it was fully automated multi-stage production line with engine blocks positioned, machined and transferred to the next stage in a sequence of custom automatic machining operations. Modern low cost computers and pneumatic systems allow these **production automation** techniques to be used today for relatively low volume production.

1951 Philip Edwin **Ohmart** of Cincinnati, Ohio, invents the first **nuclear battery** which converts radioactive energy directly to electrical energy. It consisted of two electrochemically dissimilar electrodes separated by a filling gas which was ionised by exposure to nuclear radiation to produce the electrical current. Ohmart obtained an emf efficiency of 0.01% on a cell using magnesium dioxide and lead-dioxide with argon as the gas and Ag^{110} as the radioactive source. The idea was later used by **Sampson** and **Brown** in their respective **Gamma** and **Beta** batteries.

1951 The world's first **nuclear powered electricity generating station** Experimental Breeder Reactor EBR 1, a pilot plant generating 100KW starts up in Arco, Idaho.

Nuclear power plants use a variety of fuels, moderators, coolants and reactor designs all of which are very complex but the reactors themselves do not generate electricity directly. They are simply used as **nuclear boilers** to heat water, raising steam to drive conventional turbine generators, a crude but controllable (safe) way of harnessing nuclear energy.

In 1953 Arco, population 1000, becomes the first community to be powered by a nuclear reactor. In subsequent years the use of nuclear power spread as other countries followed suit.

- 1954 Obninsk, USSR, 5MW capacity
- 1956 Calder Hall, UK, 50MW capacity
- 1956 Marcoule, France, 5MW capacity
- 1957 Shippingport, Pennsylvania, USA, 90MW capacity
- 1962 Rolphton, Canada, 20MW capacity

In 2005 there are currently 439 nuclear power plants generating 16% of the world's electricity with 25 more plants under construction and over 100 more planned or proposed.

1951 Russian nuclear physicists Igor Yevgenyevich **Tamm** and Andrei Dmitriyevich **Sakharov** working at the Kurchatov Institute of Nuclear Fusion proposed a method of generating nuclear power by means of controlled **thermonuclear fusion** by bringing gases together in an extremely hot ionised plasma in a toroidal-shaped (doughnut) magnetic bottle, known as a **Tokamak** device. The name is an acronym of the Russian words for Torroidal Chamber Machine. The magnetic forces acting on the moving charges of the plasma keep the hot plasma from touching the walls of the chamber and the current that generates the field is induced in the plasma itself serving also to heat the plasma. The fusion fuel is different isotopes of hydrogen which must be heated to extreme temperatures of some 100 million degrees Celsius, and must be kept dense enough, and confined for long enough (at least one second) to trigger the energy release.

To date, the highest temperature produced in a laboratory was in 1994 when a **plasma temperature** of 510 million degrees Celsius (918,000,000 deg F) was recorded in the Tokamak Reactor operated at the Princeton Plasma Physics Laboratory in the USA. Despite achieving these very high temperatures it has still not been possible to create controlled self-sustaining thermonuclear fusion.

And some people thought they could achieve **cold nuclear fusion** in a beaker of heavy water.

Sakharov is possibly better known for his outspoken campaigning *against* nuclear proliferation and *for* human rights for which he was banished and kept under police surveillance.

1952 Patent issued to the **Lip Watch** Company of France for the first **electric watch**, made possible by **Ruben**'s **button cell**.

1952 10,000 **transistors** are manufactured world wide, mostly for government and research.

1952 American engineer William G **Pfann** working at Bell Labs invented the **zone refining** process for purifying Germanium to a level of one part in 10^{10} (a single grain of salt in a bag of flour would be impure by comparison). It depends on the fact that the melt of a crystalline material will sustain a higher level of impurities than the crystal itself. The Pfann process involved localised melting by induction, or other, heating of the Germanium ingot supported in a graphite boat inside a tube. By moving the heater along the tube the molten zone passes down the ingot melting the impure solid at its forward edge and leaving a wake of purer material solidified behind it. In this way the impurities concentrate in the melt, and with each pass are moved to one end of the ingot. After multiple passes the impure end of the ingot is cut off.

Pfann was apparently unaware that a single pass purification technique had been proposed in a paper published in 1928 by Russian physicist Peter **Kapitza** working for **Rutherford** at Manchester University.

Unfortunately, while Pfann's method worked fine for refining Germanium with a melting point of 937ºC, it did not work for Silicon whose melting point is 1415ºC because no suitable boat material could be found to withstand the high temperatures without contaminating the melt. The problem was solved in 1953 by Bell Labs metallurgist Henry C. **Theuerer** with the development of the **floating zone method**. He was able to create a molten zone in silicon by holding the ingot in a vertical position and moving it relative to the heating element. In this vertical configuration the surface tension of the molten silicon was sufficient to keep it from coming apart.

One of the earliest commercial products to evolve from the development of single-crystal silicon was the **Zener diode** named after its American inventor, Bell Labs physicist Clarence Melvin **Zener**. The Zener diode was the first solid state voltage regulating element.

1952 Bell Labs researcher Calvin S. **Fuller**, working initially with Germanium, published studies showing that donor and acceptor atoms could be introduced into to shallow, controlled depths in the Germanium crystal by **diffusion**. The method involved exposing the semiconductor to the dopants in high temperature vapour form. The depth of penetration of the dopant was controlled by the temperature and allowed the production of much thinner base layers and a corresponding improvement in frequency range of the device. The diffusion method was an essential milestone in the development of the **integrated circuit**.

1952 **Gallium Arsenide (GaAs)** identified as a semiconductor by Heinrich **Welker** by now working at Siemens in West Germany.

1952 English radar engineer Geoffrey W.A. **Dummer** working for the Royal Radar Establishment of the British Ministry of Defence recognised that if circuit elements such as resistors, capacitors, distributed capacitors and transistors were all made of similar materials they could be included in a single chip. In a paper entitled "Electronic Components in Great Britain", he was the first to outline the concept of the **integrated circuit** as "electronic equipment in a solid block with no connecting wires". In 1956 Dummer placed a contract with Plessey to build an integrated circuit but they were unsuccessful since the only fabrication method available to them at the time was the unsuitable **grown junction technique**.

1952 The English engineer Sir Charles **Oatley** invented the **scanning electron microscope (SEM)** in its present form. In contrast to the STM in which the electron beam is detected after passing through the specimen, the electron beam in the SEM scans the surface of the specimen and detects the electrons which are scattered back from the sample using them to build up an image. This enables it to show three dimensional images of surface texture. This capability makes it more useful than the TEM for many metallurgical applications and an essential tool in the cell designer's armoury. See also **TEM** and **STM**.

1952 English physiologist and biophysicist Alan Lloyd **Hodgkin** and Andrew Fielding **Huxley** member of the distinguished Huxley family of biologists and authors working at Cambridge with Australian research physiologist John Carew **Eccles**, discovered the chemical means by which **nerve impulses** are communicated through the body by the excitation or inhibition of nerve cell membranes. They experimented with living cells but because the **neurons** (or **axons** which carry the nerve impulses) of almost any other cells were too small to study using the techniques available at the time, they used the giant axons of the nerve cells of the Atlantic squid, *Loligo pealei*, which are over 100 times the size of human axons. By planting tiny electrodes in the cells they were able to record the ionic currents resulting from nerve impulses. They showed that the nerve impulses cause a temporary contraction of the muscle cell, expanding the minute pores in the cell membranes which allow the interchange of potassium ions in the cell with sodium ions from outside of the cell. The change in the concentrations of the ions in the cell effectively changes the electric potential difference across the cell membrane and at the same time this activates a similar action in the adjacent cell. In this way the nerve signal is passed chemically along the nerve fibre permitting transmission of the original impulse through the body, not electrically as had been **du Bois-Reymond**'s accepted theory for over 100 years. They called this the **Sodium pump** method of transmission.
They were awarded the 1963 Nobel Prize for Physiology or Medicine for their work.

1953 Microtone, Maico, Unex and **Radioear**, all in the USA introduce the first commercially available consumer product to use **transistors**. This was the **hearing aid** powered by a **mercury button cell**.

1953 Intermetall (Germany) demonstrated at the Düsseldorf Radio Fair, a **solid-state radio receiver** using four **transistrons** designed by German physicists Herbert F. **Mataré** and Heinrich **Welker** while working at Westinghouse in France.

1953 American engineer Andrew F. **Kay**, at his company Non Linear Systems, invented the **digital voltmeter (DVM)** which offered 0.01% accuracy, an order of magnitude better than analogue instruments at the time, paving the way for digital readout instruments.
In 1982 he changed the name and mission of the company to Kaypro and launched the ill fated **Kaypro II** computer.

1953 Polycarbonate plastic material discovered accidentally by Daniel W. **Fox** at GE Labs in the USA while working on a project to develop a new wire insulation material. Almost indestructible it finds use in products ranging from cell phone and battery casings to CDs and bullet proof glazing.

1954 ABS polymers were introduced to commercial markets by the Borg-Warner Corporation who had patented the **thermoplastic** product in 1948. A wide spectrum of ABS plastics can be produced by varying the proportions of the three 3 constituent **monomers** - **Acrylonitrile, Butadiene** and **Styrene**, with properties tailored to meet specific requirements. In addition to this great versatility, ABS plastics in general are distinguished by great toughness and high impact strength (even at low temperatures), good dielectric properties and excellent dimensional stability. To this is added extremely fine gloss appearance, very wide colouring and surface texturing possibilities which make it ideal for use in both consumer and technical products. It is the material of choice for most small battery pack housings.

1954 Introduction of **Styrofoam** in the USA. Like so many inventions, Styrofoam, or **expanded polystyrene** was discovered accidentally. Ray **McIntire** working at Dow Chemical was trying to find a flexible rubber-like polymer for use as an electrical insulator using polystyrene by combining styrene with isobutylene, a volatile liquid, under pressure. The result was a foam polystyrene with bubbles 30 times lighter than basic polystyrene. Now widely used for both packaging and insulation.

1954 Patent granted to **Shockley** for the use of **ion implantation** for selective doping of semiconductor materials.It used an **ion accelerator** to create a beam of energised ions of dopant atoms with sufficient energy (20 to 200keV) to penetrate into the crystal lattice. This enabled penetrations of 0.1 to 1.0 µm and the placement of precise amounts of dopants in controlled locations in the semiconductor substrate, however at the same time it also caused collateral damage to the crystal structure which had to be repaired by an subsequent annealing process. The patent was the culmination of work started in 1949 with **Ohl.** Although this method of doping allowed more precise control of the semiconductor properties than the **diffusion** method of doping and is used almost universally today, it did not take off at the time because the ion implantation equipment was very expensive and the newly developed diffusion method was simpler and more cost effective. It wasn't until the 1967 introduction by **Bower** of the **IGFET** whose manufacturing depended on ion implantation, and the availability of less costly ion accelerators, (typically $3 million or more) that the technique began gain acceptance.

Shockley's patent expired in 1974 and he derived few royalties from his invention.

1954 Using Fuller's **diffusion process**, Charles A. **Lee** at Bell Labs made the first **diffused base germanium mesa transistor** **(diagram)**. This device had a cutoff frequency of 500MHz, a factor of ten faster than the best **alloy transistors** of the time.
The **mesa transistor** gets its name from resemblance of the built up layers or structures made by the base and the emitter protruding from the surface of the wafer, to the geographical formations in Monument Valley USA. (Spanish mesa: table).

Early mesa transistors were made by diffusing the base layer dopants into a wafer of collector material. Then a patch of inert material, usually a wax, was applied to the doped surface where the emitter was intended to be and a strong acid was used to etch away the semiconductor, including the doping, from around the patch leaving a flat topped protrusion on the wafer. After removal of the patch, the surface was cleaned to reveal the base to which the emitter material was then alloyed.
Apart from the difficult manufacturing process, the mesa transistor however had other drawbacks in that the semiconductor junctions were exposed to both contamination and physical damage leading to unpredictable performance. These problems were eventually overcome by **Hoerni**'s **planar process**.

1954 Was the year of the **Silicon transistor** with breakthroughs from both Bell Labs and Texas Instruments. Germanium transistors suffered performance limitations which made it unsuitable for military applications and had still not made much impact in the consumer marketplace. Although it was more difficult to work with, Silicon was much cheaper than Germanium and allowed higher operating temperatures and higher power outputs which were important to the military who funded much of the US semiconductor research and development and it quickly replaced Germanium as the basic material for transistor production.

1954 Daryl **Chapin**, Calvin **Fuller**, and Gerald **Pearson** working at the Bell Labs demonstrated the first practical photovoltaic **solar cell** that could generate useful power using **Silicon** rather than Selenium. By diffusing a thin layer of P type Boron atoms into a wafer of N type Silicon they constructed large area **p-n junctions** which generated substantial current when sunlight fell on them, achieving **conversion efficiencies** of 6% compared with the 1% possible for the last eighty years with **Fritts**' Selenium cells. By the late 80's efficiencies of over 20% were being achieved with Silicon and Gallium Arsenide cells. In 1989 efficiencies of 37% were achieved by Boeing using lenses to concentrate the sunlight.

Although it may seem counter intuitive, large scale electrical power generation from solar energy is still more efficient and less expensive by using the captured thermal energy in an intermediate step to raise steam to drive turbine generators than direct energy conversion in photovoltaic cells.

1954 Also at Bell Labs, Morris **Tanenbaum** duplicated **Lee**'s diffused Germanium device in Silicon to make the first **diffused base silicon transistor** but the company kept this achievement under wraps. They didn't patent it because others had developed similar processes and they decided "From a manufacturing point of view, it just didn't look attractive". As a consequence they did not at the time put in place any manufacturing facility to support this new technology.

1954 The mighty Bell Labs with their superior diffusion technology were upstaged by an upstart company from Texas who announced the first successful **Silicon transistor** a **grown junction device** developed by Willis **Adcock** working with Bell alumnus Gordon **Teal** who had left Bell to work at Texas Instruments (TI) taking with him the know how he had developed at Bell Labs. The demand for this new high performance device was unprecedented, particularly from the military, but with no product availability from Bell, Texas Instruments was suddenly thrust into the big league and Teal's Silicon transistor was the spark that turned TI into the company it is today.

1954 Following the first demonstration of a **solid state radio** by Intermetall in 1953, the first "transistorised" high volume electronic product aimed at the consumer market, the Regency TR-1 AM **transistor radio** was launched in the USA. Designed by Richard C. **Koch** it was a superheterodyne receiver using just four Germanium transistors from Texas Instruments, powered by a "standard" 22.5 volt battery originally intended for tube-type hearing aids. Unfortunately it did not achieve commercial success.

1954 The first **high level programming language, Fortran** (Formula Translation) was invented by John **Backus** at IBM and released in 1957. Recognised as the forerunner of today's **software** applications. But see **Plankalkül.**

1954 George C. **Devol**, an inventor from Louisville, Kentucky, designed the first programmable industrial **robots**. In 1956, with Joseph F. **Engleberger**, a businessman/engineer whom he met over cocktails to discuss the writings of **Isaac Asimov** he founded Unimation, the world's first robotics company. The first machines were **programmable transfer machines**, or **pick and place machines** whose main use was to transfer objects from one point to another. The first industrial application was by General Motors who in 1961 used the robots for moving and positioning heavy castings on heated die casting machines. Although they were introduced as labour saving devices, one of their main virtues is the precise control, reliability and repeatability of their actions which permitted consistent, high quality manufacturing processes. They are used extensively in battery assembly operations and are essential tools for achieving high levels of product quality and reliability.

1955 Willard Thomas **Grubb**, a chemist working for General Electric (GE) in the USA developed the first **Proton Exchange Membrane (PEM) fuel cell**.

1955 Reynold B. **Johnson** and his team working at IBM produced the first ever working **hard disk drive**. The RAMAC, (Random Access Method of Accounting Control) as it was called, was very large, weighing in at one ton. Data was stored on fifty 24 inch magnetic disks coated on both sides with magnetic iron oxide and rotating at 1200 RPM on a single shaft. It used vacuum tube control electronics and a single read/write head to read data from each of the 24 platters giving a file access time averaging at about one second. Its storage capacity was 5 million characters (less than 5 megabytes since they were 7 bit not 8 bit characters), roughly the equivalent of only one song on a modern iPod. It was not until 1961 that separate heads for each platter were used. Today, all hard disk drives are based on Johnson's basic system.

1955 The **USS Nautilus**, the world's first **nuclear powered submarine** "Under way on nuclear power". A ship with a crew of 105 men, 98 metres (324 feet) long, displacing 3533 tons on the surface and 4092 tons submerged it could stay submerged for weeks and cover vast distances at high speed. It was powered by a lump of **enriched Uranium** the size of a golf ball which could keep it fully operational for several years without refueling. (One pound of highly enriched Uranium as used to power a nuclear submarine or nuclear aircraft carrier contains about the same energy as a million gallons of petrol/gasoline.)

1955 Battery manufacturers (if not carpet makers) have a lot for which to thank Zenith engineer Eugene **Polley**. He created the first **wireless TV remote control**, the **Flash-matic** which used a flashlight to activate photocells on the TV set. Now sold in their millions each year and all needing batteries, the second generation was based on **ultrasonics** and today's products use **infra red** or **radio** transmission.
The remote control started a general trend for more portability with users no longer being satisfied with being tied to the electrical mains or telephone socket outlets.

1955 Patent granted to Chinese-born US computer engineer An **Wang** for the invention of the **magnetic core computer memory**. Actually Wang's design predates that of Forrester who is also credited with the invention. Core memory was built up from tiny rings of ferro-magnetic material or **ferrite cores**, each just over 1 millimetre in diameter, through which passed a matrix of fine wires perpendicular to eachother forming an array or grid. When it was magnetized one way, a core represented a one, when magnetized in the opposite direction, it stood for a zero. Cores were **random-access** devices, which meant that individual cores could be accessed directly by addressing the appropriate wires on the grid, without disturbing any of the other cores. Wang's 1949 design used a single wire and "write after read" electronics to overcome the problem that the act of reading actually erased the memory. Forrester's design used multiple wires and the "coincident current" method of reading and writing. Magnetic core memory had been commercially available since 1953 but in the meantime, the dispute over the Intellectual Property Rights gave rise to many law suits which were eventually settled by IBM purchasing Wang's patents for several million dollars. Forrester's random access memory **RAM** design became the industry standard for the next 20 years until the advent of cheap semiconductor memory.

1955 Indian scientist Narinder Singh **Kapany** working at Imperial College, London shows that a glass-coated glass rod, the forerunner of **optical fibre** is able to transmit light over long distances with little loss of intensity. The glass coating, or cladding, prevents the light from leaking out from the core. By **Snell's Law** the lower refractive index of the cladding with respect to the core causes the light impinging on the boundary to be reflected back into the core.

1955 Arthur **Uhlir** and A.E. **Bakanowski** working at Bell Labs develop the **varactor diode** or **varicap**. These are P-N diodes used as voltage-controlled capacitors in tuning circuits including PLL (phase-locked loop) and FLL (frequency-locked loop) circuits and were used extensively in television receivers.

1955 Shockley left Bell Labs to start his own company, **Shockley Semiconductor Laboratory** (a division of Beckman Instruments). He hired a team of young semiconductor wizards but focused their attention narrowly on producing a **four layer diode** the **Shockley diode** which he had **proposed in 1950**. Intended as a replacement for the relay used by the millions by AT&T in their telephone switching circuits it was ahead of its time, complex and very difficult to produce. Frustrated at not being able to explore their own ideas or the opportunities of the rapidly expanding semiconductor industry and disillusioned with **Shockley's management style** many of his staff left. The potential applications for the four layer diode were soon captured by the newer integrated circuits and the Shockley diode was relegated to a few niche applications.

1956 The **Silicon Controlled Rectifier (SCR)** or **Thyristor** proposed by Shockley in 1950 and championed by **Moll** and others at Bell Labs was developed first by power engineers at G.E. led by Gordon **Hall** and commercialised by G.E.'s Frank W. "Bill" **Gutzwiller**. It is a four layer, three junction pnpn transistor originally conceived simply as a logic switching device but developed as a high current switch to control large amounts of power. Used extensively in motor control, dimmers and similar applications.

1957 Russia stunned the world with the launch into orbit of **Sputnik 1** (meaning "fellow traveller"), the world's first artificial **satellite**, orbiting the Earth every 98 minutes. Conceived and brought to fruition by engineer Sergei Pavlovich **Korolev**, leader of Russia's missile programme, Sputnik 1 was an 84 Kg (184 lbs) aluminium alloy sphere, 56 cms(22 inches) in diameter containing two zinc oxide batteries powering a thermal regulation system and a radio which transmitted temperature and pressure data and a "beep beep" sound which announced its presence to the world below and signalled the start of the **Space Race**.

1957 Japanese research student **Leo Esaki**, working for Sony, discovered the **tunnel diode**, the first **quantum electron device**. It depends on an effect called "quantum mechanical tunneling", discovered by **Hund** in 1927, which gives rise to the forward characteristic having a region where an increase in forward voltage is accompanied by a decrease in forward current. See **tunnel diode characteristic**. This **negative resistance** (dI/dV) region was discovered and exploited by **Losev** in the 1930's in the design of high frequency oscillators. **Tunneling** means that a particle such as an electron can pass from one side of a very thin barrier to the other without passing through the barrier. Esaki was awarded a Nobel Prize in physics for his efforts, one of only three Japanese to be so honoured. By coincidence all three had attended the same high school.

1957 The first widely-accepted theoretical understanding of **superconductivity** was advanced by American physicists John **Bardeen**, inventor of the transistor, Leon **Cooper**, and John **Schrieffer**. Known as the **BCS theory**, it and won them a Nobel prize in 1972. (The second time for Bardeen.)

1957 The first life saved by applying an electric shock to the heart using the closed chest electrical **defibrillator** designed by American engineer William Bennett **Kouwenhoven.** Ventricular fibrillation (VF) is a life threatening condition in which the heart no longer beats but quivers or fibrillates very rapidly 350 times per minute or more. A person cannot survive VF for long. Note that one cause of fibrillation is a low voltage electric shock. The defibrillator works by applying a second more powerful jolt to the heart to restore the normal rhythm. More on **electric shocks**

1957 The **Hamilton Watch** Company in the USA claims the first commercial production of **electric watches**

1957 The recombinant **Gel SLA** or **VRLA Battery** patented in Germany by Otto **Jache** working at Sonnenschein Battery. The gel impedes the release to the atmosphere of the oxygen and hydrogen gasses produced by the galvanic action of the battery during charging and promotes recombination of these gases thus reducing the loss of electrolyte and increasing the life of the battery.

1957 Patrick J. **Hanratty** working at General electric un the USA developed **PRONTO** a programming language for implementing **numerical control of machine tools**, the basis for **Computer Aided Manufacturing** and the world's first commercial **CAD/CAM software**. Modern CAD/ CAM software systems are now indispensable tools for the fast turnaround of complex product and tool designs.

1957 Carl J. **Frosch** and Link **Derrick** of Bell Labs announce their discoveries, dating from 1954, that the surface of a Silicon crystal can be readily oxidised by heating to about 1200°C in an atmosphere of water vapour or oxygen to form a stable layer of Silicon Dioxide SiO_2 , an insulator which is impervious to moisture. They showed that this **passivating layer** has three major uses. It can be used simply as a barrier to protect the semiconductor device from contamination, it can be used to mask the surface of Silicon during diffusion allowing the precise placement of dopants through windows etched in the oxide layer and it also supports the application of an overlay of metallic interconnecting circuits which it insulates from the lower layers. This latter property was essential to the development of the **planar transistor**.

During this development period in 1955 Jules **Andrus** and Walter L. **Bond** also at Bell Labs developed the **wet chemistry** process of **photolithography** employed by Frosch and Derrick. It uses **optical masks** and **photoresists** for masking and etching the oxide layer to create an **oxide mask** on the surface of the Silicon which in turn exposes only the precise areas to be doped during the diffusion process.

Advances in photolithography providing ever smaller line widths have made the **scaling** of integrated circuits possible leading to dramatically improved performance. Smaller device geometries increase the component density on the chip allowing more chips per wafer and thus lower manufacturing costs, but equally important, they also allow reduced power consumption and increased operating speed. Shorter tracks reduce the device resistance as well as the electron transit times, smaller gates decrease the device capacitance permitting higher frequency operation.

1958 PEM fuel cells improved by Leonard **Niedrach** who devised a way of depositing platinum onto the membrane, which ultimately became known as the "**Grubb-Niedrach fuel cell**." GE and NASA developed this technology together resulting in its use on the **Gemini space project** NASA's first manned space vehicles. This was the first commercial use of a fuel cell.

1958 The **planar process** **(diagram)** for manufacturing transistors invented by Jean **Hoerni** at Fairchild Semiconductor. In an attempt to solve the contamination problems of mesa transistors he diffused the junctions down into the silicon instead of building them up into a mesa. He was then able to deposit a thin layer of Silicon dioxide over the junctions to act as an insulator. Using a **photomasking process**, holes were etched open in the Silicon dioxide to permit connections to be made to the junctions. Later the addition of a metal layer enabled interconnections to be made, eliminating wires and paving the way for the **integrated circuit** (See next).

1958 Jack St. Clair **Kilby** working at Texas Instruments and Robert **Noyce** working independently at Fairchild Semiconductor invented the first **monolithic integrated circuits** (Greek: monos - single and lithos - stone) for which they subsequently applied for patents in 1959. Now simply called integrated circuits or ICs. Kilby's IC, a phase shift oscillator, was the first. It incorporated one mesa transistor, three resistors and a capacitor on a single Germanium chip but the interconnections were still by conventional welded wire leads since Kilby had not developed a way of connecting them directly through the chip.

Kilby's integrated circuit was followed six months later in 1959 by Noyce's **flip flop** IC. It is usually claimed that it was Noyce's use of the **planar process** for manufacturing the ICs, which enabled the conducting tracks for interconnecting the components to be incorporated onto the silicon substrate, that made the integrated circuit commercially successful. While this is true, Noyce also made use of another technology equally essential to the functioning of the integrated circuit. He needed a method of electrically isolating the individual devices within the IC from eachother and for this he used the concept of back to back PN junctions invented for that purpose in 1959 by Czech-born physicist - Kurt **Lehovec** of Sprague Electric.

The use of the Lehovec patent was an integral feature of the original integrated circuit chip design and remains fundamental to chip design today and although Noyce himself recognised Lehovec's contribution, the rest of the world seems to have overlooked it. While honours were heaped upon Kilby, both Hoerni and Noyce achieved **commercial fame** and fortune but the forgotten Lehovec is reported to have said "I never got a dime out of [the patent]."

Although Kilby was first to file for a patent, his application was rejected because it lacked a way of interconnecting the components and Noyce was granted the first patent in 1961. After protracted legal battles, Texas Instruments and Fairchild Semiconductor finally agreed to share their licensing agreements for IC's and Noyce and Kilby, by then considered as co-inventors of the IC, were jointly awarded the US National Medal of Science for their invention. Forty years later in 2000 Kilby was awarded the Nobel prize for physics in recognition of his contribution to the invention of the IC. By that time Noyce had been dead 10 years and Nobel prizes are not awarded posthumously.

1958 Invention of the **laser** announced with the publication of the scientific paper, "Infrared and Optical Masers" , by Arthur L. **Schawlow**, then a Bell Labs researcher, and Charles Hard **Townes**, a consultant to Bell Labs in "Physical Review", the journal of the American Physical Society. However Gordon **Gould** was the first person to use the word "laser". A doctoral student at Columbia University under Charles Townes, the inventor of the **maser** (a similar device based on microwave amplification rather than optical amplification), Gould was inspired to build his optical laser starting in 1958 but failed to file for a patent for his invention until 1959. As a result, Gould's patent was refused and his technology was exploited by others. It took until 1977 for Gould to finally win his patent war and receive his first patent for the laser. See also **Maiman** (1960)

1959 Canadian Lew **Urry** patented the first modern **primary** **Alkaline** **battery**. The principle on which the alkaline cell is based, substituting

Manganese Dioxide for Mercury Oxide in the Ruben cell, was discovered in the late 1940's just after World War II but it took nearly twenty years of development before the product as we know it today was introduced by Ever Ready and Duracell between 1968 and 1970.

1959 Harry Karl **Ihrig** of Allis-Chalmers, an American farm equipment manufacturer, demonstrated the first **fuel cell powered vehicle** using 1008 cells to provide 15kW.

1959 Richard Phillips **Feynman** published "There's Plenty of Room at the Bottom" describing the manipulation of individual atoms, outlining the principles of **nanotechnology** though it was not called that at the time.

1960 Physicist Theodore Harold **Maiman** working at Hughes Research Labs developed, demonstrated, and patented the first commercially successful operable **laser**, a device which produces monochromatic coherent light, using a pink ruby medium for which he received worldwide recognition. Amongst its many applications, laser technology is used for fibre optic transmitters, holography, range finders and for precision cutting and welding (the sealed metal cases of energy cells are welded by lasers).

1960 Dawon (David) **Kahng** and Mohammed (John) **Atalla** at Bell Labs invented the **metal oxide semiconductor field-effect transistor (MOSFET)**, a new implementation of the FET in **planar** form in which the metallic gate was insulated from the semiconducting channel by an insulating layer of Silicon dioxide. PMOS and NMOS MOSFETs were cheaper, smaller, and less power-hungry than bipolar transistors but the first designs were also slower and took a long time to gain market acceptance.

Two years later in 1962 Stefan R. **Hofstein** and Frederick P. Heiman, two young engineers at RCA's research laboratory incorporated the MOSFET design into the first **MOS integrated circuit** consisting of 16 silicon n-channel MOS transistors.

Pioneering work on MOSFETs was also carried out in 1961 at Fairchild by quiet Chinese physicist Chih-Tang **Sah**, (known as "Tom"), another **Shockley** alumnus who had followed the "traitorous eight" to Fairchild.

The 'Metal' in the name is an anachronism from early devices where gates were metal, usually aluminium. In modern chips the gate electrode is formed from **polysilicon** (polycrystalline Silicon) which is also a good electrical conductor but which can better tolerate the high temperatures used to anneal the silicon after **ion implantation**, however they are still called MOSFETs

1960 Epitaxial deposition or **epitaxy** (Greek: epi - on and taxis - arrangement) developed by H.H. **Loor**, H. **Cristensen**, J.J. **Kleimack**, Henry C. **Theuerer** and Ian Munro **Ross** at Bell Labs for growing a new crystal layer of one material on the crystal face of another (heteroepitaxy) or the same (homoepitaxy) material, such that the two materials have the same crystallographic orientation as the substrate. Very thin crystal layers can be built up in this way allowing better control of the doping thickness and abrupt changes in the doping concentrations providing doping profiles unobtainable with other methods. The substrate is unaffected by the process and may be designed for optimum mechanical strength or thermal conductivity. Performance could be optimised for both high frequency and high power by having a thin base layer and a low resistivity collector on a substantial substrate.

In 1968 Alfred Y. **Cho** and John R. **Arthur** also working at Bell Labs perfected **molecular beam epitaxy (MBE)**, an ultra-high vacuum technique that could produce single-crystal growth one atomic layer at a time.

1960 After 3 years of development Wilson **Greatbatch** an American electrical engineer launched the world's first totally implantable **heart pacemaker** made possible by the use of a long life **Lithium Iodine primary battery** which he also developed. Today over 3 million people around the world have electrically powered implants and over 500,000 new pacemakers alone are installed every year.

1960 Ivan **Sutherland** working at MIT's Lincoln Laboratory developed **Sketchpad**, which used a **light pen** to draw on a computer's monitor. It is considered the first step towards **Computer Aided Design** and the basis on which many commercial **CAD** packages were founded.

1960's The construction of high energy **zinc air button cells** made possible by the use of very thin electrodes and **Teflon** insulation.

1960's Two 1.5 kW **alkaline fuel cells**, based on the **Bacon** patents, provided electrical power and much of the drinking water for NASA's **Apollo spacecraft** which went to the moon.

1961 The U.S. Department of Energy (DOE) provides **Radioisotope Thermoelectric Generators (RTGs)** for **NASA**. RTGs are **Nuclear batteries** which generate electrical power from radiation emitted by the decay of certain **radioactive isotopes**. They are used for space applications and power to unmanned remote installations such as lighthouses.

1961 American engineer Robert H. **Riley** working at **Black & Decker** invented first **cordless electric drill**. Because of the the limitations of the Nickel Cadmium batteries available at the time, Riley's first 4.8 volt cordless drills could only produce 10 to 20 watts, compared with the 200 to 250 plus watts of the conventional mains powered drill. To compensate for the lack of power, more efficient motors were designed and gearing was used to increase the torque but the designs were too expensive to be commercially successful although some more powerful versions were used in the 1960's US Gemini and Apollo space programmes. It was not until 1985, with the advent of the **Skil screwdriver** which was aimed at a less power hungry application, that the demand for cordless power tools finally took off.

1961 96% of British homes wired for electricity.

1961 Rudolf Emil **Kalman**, a Hungarian working at the University of Columbia in the USA, developed the **Kalman Filter**. A mathematical technique which enables accurate information to be derived from inaccurate data, it is used in complex control systems with multiple inputs. Initially developed for use in **predictive control systems**, chasing moving targets, it also finds use for **BMS** State of Charge determination.

1961 The availability of integrated circuits on single **monolithic chips** paved the way for the digital revolution enabling the production of low cost logic circuits. Over the years, more and more logic functions were incorporated into single chip packages and a series of **logic families** was developed as improvements to the semiconductor technology were made. Some major developments are outlined here:

- **1961 Resistor-transistor logic (RTL)**

  Noyce's team at Fairchild introduce the first commercial integrated circuit a set-reset **flip-flop**, the first of a family of logic circuits built from **bipolar junction transistors (BJTs)**, and resistors. RTL circuits are made up from transistors and resistors arrayed to carry out NOT-OR and

NOT-AND functions. Although the technology had its limitations and was soon superseded by more efficient designs it was old reliable RTL which was used in the Apollo computer and guidance system which took the astronauts to the moon and back in 1969. RTL is now obsolete.

- **1962 Diode-transistor logic (DTL)**

  A breakaway team who had left Fairchild to form Signetics, subsequently led by Orville **Baker**, announced a second generation logic family which incorporated diodes into the input circuits of the transistor switches increasing the circuit functionality as well as the logic gate **fan-in** (the number of inputs which can be connected to the gate) and improving the noise immunity.

  RTL and DTL logic circuits were direct implementations in Silicon of the equivalent circuits made with discrete components wired together on a circuit board and the rapid impact of the technology was in part due to its familiarity with applications engineers.

- **1962 Transistor-Transistor Logic (TTL or T^{2}L)**

  The basic principle of TTL logic was proposed by James L. **Buie** working at Pacific Semiconductors, but the credit for the invention was taken by Thomas A. **Longo**, working at Sylvania, who turned the idea into practical devices which he showed at Wescon. They were **bipolar** devices and had high speed, but suffered from poor noise immunity. The transistor output in a TTL device is connected directly (rather than through a resistor or diode) to a transistor input of the next stage.

  TTL logic was the first to use the potential of the integrated circuit to produce devices which were not possible at the time with discrete components. The switching action of a TTL gate is based on a **multiple-emitter input transistor** which replaces the array of input diodes of the earlier DTL logic giving improved speed and a reduction in chip area. TTL is fast but power hungry, creating heat dissipation problems in dense circuits and heavy demands for battery power. It made new circuit configurations possible however and dominated the microelectronics industry through the sixties and into the seventies, when it was largely displaced by CMOS logic in large-scale integration.

- **1962 Emitter coupled logic (ECL)**

  A bipolar logic design pioneered by Jean **Aroot** at Motorola. Also called **Current Mode Logic (CML)**, it is the fastest logic family currently available. It operates the transistors in a non-saturating mode, unlike TTL where transistors are either cut off or saturated. ECL is thus faster than TTL but it consumes even more power.

  The ECL logic input is applied to one side of a differential amplifier which has a fixed bias on the other input. See **diagram**. Since the transistors are always in the active region, they can change state very rapidly, so ECL circuits can operate at very high speed but it also means that the transistors draw substantial amount of power in both states (one or zero) generating large amounts of waste heat. ECL logic also permits a large **fan-out** (The number of parallel external circuits which the logic gate can drive).

- **1963 Complementary metal oxide semiconductor (CMOS)**

  Frank **Wanlass** working with C.T. **Sah** at Fairchild realised that a **complementary circuit** of NMOS and PMOS would draw very little current and published the idea of **CMOS logic**. CMOS shrank standby power by six orders of magnitude over equivalent bipolar or PMOS logic gates and reduced battery power requirements accordingly. Early designs were slower than TTL and sensitive to damage from static discharge but these problems have been overcome. As well as low power dissipation, CMOS also has a small physical geometry permitting very high component densities. CMOS made large scale integration possible and now forms the basis of the vast majority of all high density ICs manufactured today.

- **1969 Bipolar CMOS (BiCMOS)**

  The problems of integrating bipolar and MOS transistors into a single device overcome by a team led by **Lin** Hung Chang who publish their design for "Complementary MOS-Bipolar Transistor Structure" at the IEEE - IEDM.

1962 The first solid state **op-amps** were introduced by Burr Brown and G.A. **Philbrick** Researches, but it was designs by Bob **Widlar**, working in partnership with Dave **Talbert** at Fairchild which caused the demand to take off. Widlar avoided using resistors and capacitors where possible using diodes and transistors instead. In particular, dc-biased transistors were used in place of high value resistors. His first design launched in 1963 contained just nine transistors and sold for $300. The op-amp is now the work horse of **linear circuits**.

A brilliant and prolific designer, Widlar was a larger than life, nonconformist character with a prodigious capacity for the consumption of alcohol. He left Fairchild to join the fledgling National Semiconductor when his boss Charles E. **Sporck** refused to reflect his perceived worth to the company in his pay packet. A year later Sporck himself moved to National Semiconductor as president becoming Widlar's boss once more, but Widlar's compensation package was by then secure. When a budget crunch led Sporck to stop all expenditures, from buying new pencils to mowing National's lawn, Widlar brought in a sheep in the back seat of his Mercedes-Benz convertible to cut the grass. He retired at the age of 29.

1962 American Nick **Holonyak**, the first student of **Bardeen**, now working at G.E. Labs, using Gallium Arsenide Phosphide (GaAsP), invented the first practical **light-emitting diode (LED)**. He also invented the first **semiconductor laser** to operate in the visible spectrum. Long life light sources, LEDs are now used in displays, remote controls and lasers.

The light emitting properties of semiconducting diodes were first discovered by **Round** in 1907 but were treated as a curiosity until they were rediscovered in 1922 by **Losev** who started in depth investigations on semiconductor diodes.

1962 Brian D. **Josephson**, a graduate student at Cambridge University , predicted that electrical current would flow between two **superconducting materials** - even when they are separated by a non-superconductor or insulator. This phenomenon is today known as the "**Josephson effect**" and has been applied to electronic devices capable of detecting even the weakest **magnetic fields**.

1962 Rachel **Carson** published "**Silent Spring**" exposing the hazards to the environment of the pesticide DDT. Coming almost 100 years after the **Alkali Works Act**, it raised once more the awareness of the complacent, or more likely the uninformed, public about the dangers of the unrestricted use and disposal of toxic chemicals and the need to protect the environment. It replaced complacency with concern and led directly to the upsurge of the **conservation and environmentalist movements**.

This was both a threat and an opportunity for battery manufacturers. On one hand they extract and process vast amounts of chemicals which their customers eventually dispose of as waste, some of it toxic, and this needs to be regulated and made safer. Already the use of some chemicals such as mercury and cadmium have been banned or restricted. On the other hand battery power is being promoted for transport applications where it can reduce the overall consumption of fossil fuels and the emission of "**greenhouse gases**", first identified as a problem by **Arrhenius** in

1896. In some cases, if batteries can not eliminate pollution, at least they can move it away from population centres or enclosed spaces to remote generating plants. Another benefit has been the establishment of **recycling** to make better use of the world's resources.

1963 South African-born American physicist Allan McLeod **Cormack** published the first of two papers, (the second in 1964), outlining the theoretical foundations of **computerised axial tomography (CAT) scanning** for making detailed X-ray images of cross-sections of the head but his papers generated little interest at the time. Unaware of Cormack's work, in 1972 British electrical engineer Godfrey Newbold **Hounsfield** a radar specialist in the Royal Air Force during World War II, built the first CAT scan machine. The scanner sends hundreds of X-ray beams at different angles through the brain or body and uses a computer to construct detailed cross section images from the received data and a three dimensional analysis of the body's organs can be made from a series of these X-ray cross sections. For their independent efforts, Cormack and Hounsfield shared the Nobel Prize for Physiology or Medicine in 1979.

1963 John **Gunn**, working for IBM, invented the **Gunn diode**. It is a negative resistance device used to make cheap microwave oscillators and was one of the first important applications for the semiconducting material Gallium Arsenide.
Remember Mr Gunn if you are caught speeding in a Radar trap.

1964 Working independently on entirely different problems and unaware of eachother's work, Paul **Baran** a Polish immigrant at the RAND Corporation in the USA and Welsh born mathematician Donald Watts **Davies** at the UK National Physical Lab (NPL) each came up with the idea of **packet switching** which coincidentally solved both of their problems.

Baran published first in 1964. It was during the Cold War and the US was afraid that their telecommunications network was vulnerable to attack during a nuclear war. If one or two major cities were hit, it could paralyse a major part of the network. Baran's job was to provide a resilient and secure network which could keep on working even if a major part of it was damaged.

Davies' task was to make more efficient use of the existing **Public Switched Telephone Network (PSTN)**, particularly for data communications betwen computers through **time sharing** techniques. Traditional **circuit switching** techniques used for the PSTN made inefficient use of network resources. They allocate a fixed circuit between the subscribers for the duration of the call even though the channel is most likely unoccupied for most of the time. In voice communications this is because one party is listening while the other is transmitting and even during transmission there are gaps in the speech. Data communications on the other hand have different characteristics tending to send or receive data in short bursts followed by periods of inactivity. Davies published his alternative networking scheme in 1966.

Packet switching was the solution they both arrived at. It works as follows:

- All messages are digital.
- The sender's data are chopped into packets, each with its source and destination address, and the packets are launched onto the network.
- The packets find their own way across the network, depending on circuit availability and congestion, directed by routers which read the addresses and send the packets on via the best available route. Individual packets from the message may even take different routes across the network.

- Messages are reassembled at the destination and any missing packets are re-sent.

It has the following advantages:

- Messages can be re-routed around damaged, congested or inactive switching centres.
- Data streams can be merged so that several subscribers can make simultaneous use of the channel enabling more efficient use of the network.
- It is error free although it may suffer delays.
- Communications are scrambled making eavesdropping difficult.

Packet switching was the fundamental communications technology which enabled distributed computer networking and thus the building of the **Internet**.

It was not until 1973 however that work started on standardising packet switching communications protocols to permit any network to connect to any other. It was TCP/IP that enabled this and thus the spectacular growth of the Internet.

1964 Patent for the first **super flywheel battery** issued in Russia to Dr. N.V.**Geulia**. (See Flywheels)

1964 The **printed circuit motor** also called the **pancake motor** patented by French inventor J. **Henti-Baudot**. It is a fast acting ironless core motor useful for servo applications and industrial controls.

1964 Americans Donald L. **Bitzer**, Gene **Slottow**, and Robert **Wilson**, working at the University of Illinois, and searching for a flicker free screen which did not need constant refreshing, invented the **flat plasma display** panel. It consisted of three layers of glass. The centre layer had rows of tiny holes with a mixture of gases in them. Each outer sheet had thin, transparent metallic lines on its outer surface. The lines of each sheet were at right angles to the lines of the other sheet, and a gas-filled hole was found at each point where the lines crossed. The two grids carried a high-frequency electrical voltage sufficient to maintain a glow in the tiny gas cells but not sufficient to start the glow. An electrical signal applied to any pair of lines "turned on" the glow of that cell where the lines intersected, and the sustained voltage maintained the glow until another electrical signal turned it off. Exciting the gases trapped in the grooves and sandwiched between the glass plates created the screen images.

Ironically Bitzer was presented with the 1973 Vladimir K. Zworykin Award from the National Academy of Engineering, which honours the inventor of the **iconoscope** which the plasma screen replaces.

1965 Concept of Fuzzy Logic controls proposed by Lotfi A **Zadeh** at the University of Berkley in California. A method of deriving precise information from vague data. Also used for BMS State of Charge determination.

1965 Jim **Russell** working at Battelle Memorial Institute devised an **optical disk data storage** system using digital encoding for recording and playing back music. The system was patented in 1970 but Battelle could see no future in it and sold the patents for US$1 million to a company called Optical Recording Corporation (ORC) started by venture capitalist Eli **Jacobs** in1971. Jacobs hired Russell and a number of his colleagues and provided the necessary funding for them to demonstrate a working prototype to Philips and Sony in 1974 but the consumer electronics giants too seemed unimpressed. Three years later, Philips and Sony joined forces to develop the **compact disk (CD)** which they launched on the market in 1982. By 1985 Russell had earned 26 patents for **CD-ROM** technology. Nevertheless Philips maintains to this day that their Klaas **Compaan** and Piet **Kramer** invented the CD despite having settled in 1988 for US$30 million, ORC's claim for patent infringement.

1965 The **Fast Fourier Transform (FFT)**, originally devised by **Gauss** in 1805, was rediscovered by J. W. **Cooley** of IBM and John W. **Tukey** of Princeton who published a paper describing how to perform it conveniently on a computer. The FFT samples a time varying analogue signal and converts it into its frequency components which can be represented digitally for subsequent analysis or processing. It resulted in an explosion of practical applications which could now be performed by **digital signal processors (DSP's)** which had been previously impractical to implement with analogue hardware.

1965 Gordon **Moore**, co-founder of Intel, made the empirical observation that the number of transistors per square inch on integrated circuits had doubled every year since the integrated circuit was invented and predicted that this trend would continue for the foreseeable future. This was dubbed by the press as **Moore's Law**. In subsequent years the pace has slowed down slightly and in 1975 Moore revised his prediction to doubling approximately every 18 months, a prediction which still holds good. Great for consumers, but the consequence for anyone operating in a business making or using integrated circuits is that they need to be both highly innovative and extremely fast moving.
There must ultimately be a limit to this miniaturisation however as, with nanotechnology, circuit elements are beginning approach the size of molecules and atoms.
See Intel's **Itanium 2** processor.

1965 The first working **IMPATT diode** a powerful solid state microwave generator was made by R.L. **Johnston**, Bernard C. **De Loach** and B.G. **Cohen** working at Bell Labs based on ideas originally proposed by **Shockley** in 1954.

1966 Tom **Longo**, by now working at at Transitron, developed a 16 bit **Static Random Access Memory - SRAM** chip using TTL technology, the first multi-cell dedicated memory chip. SRAM memory uses the well known **flip flop** circuits to store the bits and although the flip flop itself can be implemented by only two transistors, each memory cell actually uses four more transistors to control the read and write cycles giving a total of six transistors per cell. Up to that time with the available manufacturing technology it had only been possible to incorporate a few transistors into an integrated circuit and a typical IC with six transistors could only store one bit. It was another four years before **semiconductor memories** became a serious competitor to the slow, bulky and power hungry **ferrite core memory**.

1966 The single transistor **Dynamic Random Access Memory - DRAM memory cell** invented by IBM researcher Robert **Dennard** as a simpler alternative to the multi-transistor **SRAM memory cell** used by Longo (above). DRAM uses the presence or absence of a stored charge on a capacitor to represent a bit and a single FET to control the process. With such a low component count it is simpler and less expensive to make and occupies less space on the semiconductor chip allowing a higher packing density. The charge on the capacitor however will tend to drain away so it must be constantly refreshed adding complexity to the external circuitry. In parallel with DRAM it also took four years to scale the design up to achieve practical high density multi-cell memory chips.

1966 Neil **Weber** and Joseph T. **Kummer** working at the Ford Motor Company demonstrate the **Sodium/sulphur** battery system for EV applications, expected to achieve fifteen times the energy density Lead Acid storage batteries.

1966 The Committee on Data for Science and Technology **CODATA** established in France as is an interdisciplinary Scientific Committee of the International Council for Science **ICSU**, to determine internationally accepted values for all fundamental **physical constants**. See the results at **CODATA** 1998.

1966 Chinese born engineer Charles K. **Kao** and English engineer George **Hockham** working at STC Labs in England demonstrate that light passing down a **fibre optic** strand, which they called an **optical waveguide**, can be used to carry data over a short distances in the laboratory. They predicted that **fibre optic communications** would be possible if low loss (less than 20 dB/km) optical fibre could be developed. This means that at least 1% of the light entering a 1 kilometer long fibre should emerge at the other end. At the time the best available optical fibers exhibited losses of 1,000 dB/km or more.

1966 President Charles **de Gaulle** opened the world's first, and still the most powerful **tidal power station** at **Rance** estuary, in Brittany. The Rance plant has 24 reversible 10,000 kilowatts power units which permit the tidal flow to work in both directions, from the sea to the tidal basin on the flood and on the ebb from the basin to the sea. About seven-eighths of the power is produced on the more controllable ebb flow.

It is sad that the only name which remains indelibly associated with this engineering marvel is that of a politician rather than the names of the engineers who conceived on built it.

Although Rance was the first power station, **tidal mills** were known to be in use from Roman times until the time of the Industrial Revolution.

1967 Development work on the **recombinant, sealed-lead acid (SLA) battery** based on AGM technology was begun in 1967 by subsidiaries of The **Gates** Corp, 10 years after the **Jache** patent.

1967 Dawon **Kahng** and Simon M. **Sze** of Bell Lab proposed the first **non-volatile memory** device which holds the programmed values indefinitely or until deliberately erased. The ancestor of all programmable logic and memory it used **floating gate devices** to store the information.

1967 in search of ever finer line-widths, IBM engineers R.F.M. **Thornley** and Michael **Hatzakis** publish "Electron optical fabrication of solid state devices" in which they outline the process of **electron beam lithography** for the production of semiconductor process masks. The system uses a focused electron beam similar to that used in an electron microscope to expose polymer resist masks. Because of the shorter wavelengths of the electron beam, very complex device patterns with nanometer size resolution can be created, superior to those possible with optical lithography. Unlike optical masks however which can be exposed with a single flash of light, the electron beam must trace out the pattern which slows down the process.

1967 Fairchild's Rob **Walker** introduced **Micromosaic**, the forerunner of the **Application-Specific Integrated Circuit (ASIC)**. It was a logic chip with about two thousand transistors arranged into groups forming 150 freestanding AND, OR and NOT gates and transistors which were initially not connected to each other. The user specified the functions the circuit was to perform and a **Computer-Aided Design (CAD)** program, developed by Jim **Koford** and Ed **Jones,** would determine the necessary interconnections between the gates or transistors and generate the photo-masks required to produce the associated aluminium overlay which completed the connections. Since the creation of the aluminium interconnections is one of the last steps in the IC fabrication process, customizing the Micromosaic was not especially expensive. The initial layers of the chip were made in the normal way and only the final photomask for making the interconnections had to be custom-made. Nowadays custom chips may involve many more layers and processes.

Micromosaic was the first real application of **computer aided design**.

1968 A group at RCA, headed by George **Heilmeier**, demonstrated the first operational **Liquid Crystal Display (LCD)** based on the **dynamic scattering mode (DSM)**. See also **Reinitzer** (1888) and **Dreyer** (1950)

1968 American mathematician Donald Ervin **Knuth** published Volume 1: **Fundamental Algorithms** of his monumental work **The Art of Computer Programming** followed in 1969 by Volume 2: **Seminumerical Algorithms** and finally Volume 3: **Sorting and Searching** in 1973. The books rapidly became the software engineers' bible, now known as "TAoCP". Two more volumes are in the pipeline.

1969 The **Apollo 11** spacecraft which took the US astronauts Neil **Armstrong**, Michael **Collins** and Edwin E. "Buzz" **Aldrin** Jr. on their historic **moon landing mission** used two identical flight control computers, one in the command module and one in the lunar module, to collect and provide flight information and to control their navigational functions. Called the **Apollo Guidance Computers (AGC)**, they were developed for the Apollo program by the MIT Instrumentation Laboratory under Charles Stark **Draper**, pioneering inventor of inertial navigation sytems, with hardware design led by Eldon C. **Hall**.

The AGC was the first flight control computer to use integrated circuits (ICs). For reliability reasons the computer used only one type of IC containing a single 3-input NOR logic gate implemented with tried and tested resistor-transistor logic (RTL) technology and 4100 of these were used. For memory the computer had 4K x 16bit words of magnetic core RAM and 32K words of core rope memory for ROM. The clock speed was 2.048 MHz. The user interface consisted of an array of seven segment electroluminescent numeric displays and a numeric keypad. Instructions and data were entered manually using two-digit numeric codes.

Skillful, efficient software enabled the spacecraft to be piloted to the moon and back using the computing power of a modern day domestic washing machine. Today's engineers would do well to remember this when they demand powerful microprocessors with megabytes of memory to accomplish the simplest of tasks.

Prior to the Apollo programme, the **Mercury** spacecraft, flew in 1961 without an on-board computer. The **Gemini** spacecraft (1965-66) were the first to use on board computer guidance for which they employed a computer with only 4K words of memory.

1969 James **Fergason** at Kent State University in Ohio discovered the **twisted nematic field effect** in **liquid crystals**, and in 1971 he produced the first commercial LCDs based on this effect. These displays superseded the poor-quality DSM types.

1969 American George E **Smith** and Canadian Willard S **Boyle** while working at Bell Labs on semiconductor memory devices discovered that the semiconductors could be made photosensitive and invented the **Charge-Coupled Device (CCD)** the first **semiconductor image sensor**. This device made low cost **digital cameras** and **camcorders** possible. The first commercially available CCD image sensor was produced in 1973. The image sensor performs five key tasks: It absorbs photons, it generates a charge (electrons) from the photons, it collects the charge, it transfers the charge across the chip, and it converts the charge to a voltage.
However the high current demands of the CCD image sensor coupled with the LCD viewfinder, (and motors in the case of camcorders), ate up batteries at alarming rates. Later developments of **CMOS image sensors** cut the sensor power consumption as well as the device costs, with only a slight penalty in image quality, and boosted demand for the digital photography. Thus the battery consumption per camera was reduced but the overall demand was increased.

1969 After ten years of research and development headed by Tsuneya **Nakamura**, Seiko produced the first **quartz wristwatch** to be sold to the public. Based on technology pioneered by **Marrison** in 1927 and powered by miniature Silver oxide **button cells**, their simplicity and superior time-keeping soon made mechanical watches obsolete.

1970 George **Gray** and colleagues working at Hull University developed stable **liquid crystal materials** whose optical characteristics could be controlled by voltage rather than heat enabling the development of practical LCD displays.

1970 Engineers Robert D. **Maurer**, Donald B. **Keck**, Peter **Schultz** and Frank **Zimar** working at the Corning Glass Works in the UK succeed in producing low loss (17 dB/km) optical fibres by doping the glass core with Titanium making practical fibre optic communications possible. It was the purest glass ever made.
A **target** of less than 20 dB/km loss had been set to make fibre optic transmissions practical. A loss of only 17 dB/km gave them double the desired output.

1970 Intel and Fairchild both introduce **semiconductor memory** ICs which soon replaced the slow and expensive **ferrite core memory**.

- Intel launched the first 1Kbits **Dynamic RAM (DRAM) chip**. It was based on **Dennard**'s **DRAM cell** concept, however scaling up the single cell design into an integrated circuit involved a multi-skilled team. In this case the original concept for the 1K chip came from by William **Regitz** ex Honeywell, the cell design was improved at Intel by Ted **Hoff** and Ted **Rowe**, the chip design was carried out by Bob **Abbott**, the overall circuit design was developed by Leslie **Vadasz** and Joel **Karp** and the product engineer, John **Reed** had to make several revisions to the part before acceptable yields and performance were achieved.
- Fairchild launched the 256 Kbits **Static RAM (SRAM) chip** designed by Hua-Thye **Chua** using **Longo**'s **SRAM cell** concept. SRAM uses six transistors per cell and is thus more complex and expensive than DRAM however the external circuitry is simpler because the cell does not require refreshing because the cells do not lose their data so long as the power is not turned off or until new data is written into the cell. Static RAM is also faster than dynamic RAM, despite its name.
- In 1971 Intel launched the 2 Kbits **Erasable Programmable Read-Only Memory EPROM**. Designed by Dov **Frohman**, it was based on the

floating gate technique proposed by Kahng and Sze at Bell Labs. The memory is programmed electrically. **UV EPROMs** incorporate a quartz window which allows the information to be erased by exposure to ultra violet light while the **One Time Programmable OTP** versions do not have the erase facility. In mid-1980s the newer bulk-erasable **flash memory** replaced the EPROM.

1971 Introduction of the world's first single chip **microprocessor**, the **Intel 4004**.
In 1969 Intel were asked by Japanese calculator company Busicom to produce a set of 12 custom chips to be used in desktop calculators. Marcian "Ted" **Hoff** at Intel decided that the calculator functionality could best be implemented with a programmable solution running on a general purpose processor. With Stan **Mazor**, Hoff designed the system architecture incorporating a simple 4 bit processor using relatively few transistors and a suitable instruction set to run on it. By changing the software the device could be used for other applications. In 1970 Federico **Faggin** who had recently joined Intel was assigned the task of turning the architecture into silicon. The resulting product was a 3 chip set with a 2 kbit ROM chip, a 320 bit RAM chip and the 4 bit processor each housed in a 16 pin DIP package. Named the 4004, the processor contained 2,300 transistors and ran at a clock speed of 108 kHz.
Busicom were initially less than impressed with Hoff's departure from their original specification and with his wondrous new device and asked that Intel deliver the 12 chip set they had originally asked for. However they ultimately recognised the power and versatility of his solution and agreed to use it. Production commenced in 1971.

Hoff's concept of **programmable devices** created a revolution in electronics and ever more powerful processors quickly followed as the potential of the microprocessor was realised.

The Intel 4004 was designed by three men in less than a year. Ten years later the Intel iAPX 432 one of the first 32-bit microprocessors, unveiled in 1981, took a hundred man-years and many millions of dollars to design.

1971 Alan **Shugart** working at IBM introduced the **floppy disk,** the first portable "memory disk" as it was called then. It was an 8 inch flexible plastic disk coated with magnetic iron oxide and had a capacity of 200K bytes. In 1976 Shugart, by then working in his own company, followed up with the 5 1/4 inch flexible disk drive and diskette for Wang Laboratories. In 1981, Sony introduced the first 3 1/2 inch floppy drives and diskettes. Now most of these mechanical devices have been replaced by semiconductor memory chips.

1971 Patent for the **Gamma Electric Cell** awarded to black American research engineer Henry Thomas **Sampson** working at the US Naval Weapons Center. This device is based on principles pioneered by Ohmart in 1951 and uses a source of nuclear radiation surrounded by dielectric materials arranged to capture the radiation thus producing a **high voltage energy cell** or **nuclear battery**.
See also the similar **Betavoltaic cell**

1972 Experimental **Sodium/sulphur** battery operating at 350 °C delivering 50kWh installed in a commercial electric vehicle.

1972 The **C programming language** was developed at Bell Laboratories by Dennis **Ritchie**. Many of its principles and ideas were taken from the earlier language **B,** developed by Ken **Thompson**,also at Bell Labs. B in turn had evolved from its earlier ancestor **BCPL** (Basic Combined

Programming Language) developed in 1967 by Martin **Richards** at Cambridge University in the UK. Continuously improved over the intervening years C is now the language of choice for many **embedded software** applications such as those used in battery management. Thomson and Richie had earlier developed the **UNIX Operating System** which saw its first commercial implementation in 1971.

1972 Launch of the **digital multimeter (DMM)** by **Chauvin Arnoux**

1973 Martin **Cooper** of Motorola, is considered the inventor of the first modern portable telephone handset. Cooper made the first call on a **portable cell phone** in April 1973 to his rival, Joel Engel, Bell Labs head of research. Later the same year he set up a **base station** in New York though it took until 1977 before a network was available to use the phones.
The mobile phone alone has created a demand for over 500 Million batteries per year. This in turn has spurred on the development of new battery technologies.

1973 A group headed by Vinton **Cerf** from Stanford and Robert **Kahn** from the US Government Defense Advanced Research Projects Agency DARPA (previously ARPA), began work on addressing the problems of communications between the many independent or proprietary computer networks wishing to communicate with eachother. Although individual computer networks may have used **packet switching** for internal communications, up to that time there were no standards for packet, data and address lengths or signalling systems, so interconnection between networks was not possible. Cerf and Kahn developed the protocol later to be called **TCP/IP** to standardise the packet switching communications between computers and networks to facilitate universal interconnection.
IP - Internet Protocol specifies how data is cut up into packets and addressed to its destination.
TCP - Transmission Control Protocol ensures that data packets are reassembled in the order in which they were sent and that missing packets ar re-sent.

After ten years of development and negotiations with network users and providers, on 1 January 1983 the US Government's ARPAnet, and every network attached to the ARPAnet, officially adopted the TCP/IP networking protocol. From then on, all networks that use TCP/IP are collectively known as the **Internet**.
It was still some years more however before Europe formally adopted these standards. The **International Standards Organisation (ISO)** was trying to promote standards developed by the **Open Standards Initiative (OSI)** but the organisation was plagued by the need to satisfy the self interests of its member nations. As they aspired to the perfect system, decisions took a long time to negotiate and were often political. Meanwhile they were overtaken by events as TCP/IP gained acceptance by default while they dithered.

The reason the Internet is dominated by the Americans is that when they found a solution that worked they standardised on it and moved on, whereas in Europe, national interests had to be satisfied in the search for perfection. Ben **Segal** who introduced the Internet to CERN commented - "The time constant of the ISO committees was longer than the time constant of the technology".

The standardisation of TCP/IP gave rise to the exponential growth of the Internet. The next major development was the **World Wide Web**.

1973 Engineers at Perkin Elmer (now SVG Lithography) introduce the **projection printer** for exposing semiconductor process masks, replacing the previous method of contact printing. The combination of projection printing, without mask-wafer contact, with positive photoresist revolutionized photolithography, dramatically reducing defect rates and improving yields.

1974 Paul **Werbos** brought together research from several sources to develop a **neural network** model which is the basis of many of today's "**self learning**" applications.

1974 The **semiconducting properties of organic materials** discovered and their use as the basis for a bistable switch patented by John E. **McGinness**, Peter **Corry** and Peter H. **Proctor** working on **melanin** at the University of Texas.
Three years later, without citing the Texans' prior art, **Heeger, MacDiarmid and Shirakawa** published a similar paper, for which they were subsequently awarded the Nobel Prize.

Mid 1970's Development of the **sealed lead acid (SLA)** or **valve regulated lead acid (VRLA) batteries** invented by **Jache** in 1957.

1975 The **Nickel Hydrogen Battery** patented by J.D. **Dunlop**, J. **Giner**, G. **van Ommering** and J.F. **Stockel** working at COMSAT in the USA. The U.S. Navy's Navigation Technology Satellite (NTS-2), the first satellite deployed in the Joint Services NAVSTAR **Global Positioning System (GPS)** launched in June 1977 was the first to use Nickel Hydrogen batteries which were rapidly adopted for powering other **Low Earth Orbit (LEO) Satellites** and later used in the **Hubble Space Telescope**.

1975 H. Edward (Ed) **Roberts** an electronics engineer who owned MITS a small struggling electronics store made history when he developed and sold the **Altair 8800 microcomputer**, the first successful **personal computer**. It featured on the cover of the January 1975 issue of Popular Electronics magazine and was an instant hit. The Atair sold in kit form for $397 and shipped with a CPU card containing an Intel 8080 microprocessor and a one kilobyte memory card which came with only 256 bytes of memory chips and no software. Buyers were able to write short binary **machine language programs** that could be toggled in through switches on the front panel and the output was displayed as binary data on a row of LED's. It was left to Bill **Gates** to supply more practical software for the Altair machine.

Having started a revolution, Roberts sold his business two years later and returned to his native Georgia to pursue his first interest, medicine. He completed medical school and set up practice as a small town doctor.

1975 19 year old student at Harvard, William Henry (Bill) **Gates** III and his friend 21 year old Paul Gardner **Allen**, on hearing about the launch of the **Altair microcomputer**, called MITS and offered them a **BASIC interpreter** for their machine even though they didn't have one. They had neither an Altair nor the Intel 8800 microprocessor chip that ran the computer but they immediately set to work using the school's PDP-10 minicomputer to simulate the Altair and eight weeks later produced a BASIC interpreter which ran in only 4096 bytes of memory. Allen took the software on paper tape to the MITS office and loaded it onto an Altair machine which he had never seen before and it worked first time. Altair produced a 4K memory board to run the software and **Microsoft** was born.

In similar vein, in 1980 when IBM was looking for an operating system for the new Intel 16-bit 8086 CPU used on their first PC, Gates didn't have a

DOS (Disc Operating System), but he convinced IBM that he had one in the pipeline which was almost finished. Microsoft then purchased the rights to QDOS (Quick and Dirty Operating System) written by Tim **Paterson** of Seattle Computers for $50,000 and repackaged it as **MS-DOS**. It was written in of 4,000 lines of assembly language code and required only 12 Kb of memory. IBM found over 300 bugs in the first version submitted for testing.
Gates also talked IBM into letting Microsoft retain the rights to sell MS-DOS separately from the IBM PC project, a disastrous decision for IBM who at the time were considered invincible. It led to the establishment of a computer standard that IBM was unable to control which in turn enabled the creation of a market for PC clones and the spectacular rise of the "upstart" Microsoft, all at the expense of IBM.

1976 The **Apple I** single board computer kit designed by Stephen **Wozniak** a drop out from the University of California, Berkley and another college drop out, Steven **Jobs** who as an orphan (Steven Paul) was adopted by Paul and Clara Jobs. The computer was launched at Wozniak's "Homebrew Computer Club" and immediately took off. With "Woz" as the technical wizard and Jobs as the marketing mastermind, they followed up in 1977 with the **Apple II** which for the first time brought computing to the desktop, liberating it from the **mainframe** and the high priests of the IT department, creating an enormous world wide interest and demand for **personal computing**.

Apple's success gave rise to a host of imitators but only Apple has stood the test of time. Some of the personal computer brands which briefly flowered then fell by the wayside, many of which lost huge sums of money on the way, include the following:

- **Acorn, ACT, Altos, Amstrad, Atari, AT&T, BBC, Cambridge Research, Camputers, Coleco, Commdore, Compucolor, Cromemco, Data General, DEC, Dragon, Exidy, Franklin, Grid (Grundy), ICL, IMSAI, Intertec, ITT, Kaypro, Kim 1, Mark 8, Matra, Mattel, Micral, MITS, Nascom, North Star, Ohio Scientific, Olivetti, Oric, Osborne, Philips, Research Machines, Scelbi, Schneider, Sinclair, Sirius, Spectravideo, Sphere 1, SWTP, Tandy, Tangerine, Texas Instruments, Thomson, Timex, Victor, Vienna (Nortel), Zenith** and in 2005 the once invincible **IBM**, creator of the PC standard.
- There were also many other less famous names which hardly saw the light of day before they expired.

You can't say that the electronics business is not competitive.

1977 AT&T and Bell Labs constructed the first prototype **cellular telephone system** with public trials following a year later.

1977 American Alan J. **Heeger,** New Zealander Alan G. **MacDiarmid** and Japanese Hideki **Shirakawa** published their discovery of **conducting polymers** which made **solid state batteries** and **supercapacitors** with **plastic electrodes** possible as well as many applications in other fields. They were awarded a Nobel Prize in 2000 for their work.
They have been accused of **Citation Amnesia** AKA **The Disregard Syndrome** for failing to cite **prior art** by **McGinness, Corry** and **Proctor**.

1977 The first **Magnetic Resonance Imaging (MRI) body scanner** constructed in the USA by Dr Raymond **Damadian**. MRI scans differ from **Computerized Axial Tomography (CAT) Scans** which build up an image from x-rays in that there is no exposure to radiation. MRI images are also 20 to 30 times more detailed than CAT scans and can be displayed in colour.
Water constitutes two thirds of the body's weight and MRI depends on detecting differences in water content among the body's tissues and organs

which are reflected in a **Nuclear Magnetic Resonance (NMR)** image. "Nuclear" was later dropped from the "MRI" name to avoid frightening the patients.
The nuclei of the hydrogen atoms in the water are able to act as microscopic compass needles. When the body is exposed to a strong magnetic field, the nuclei of the hydrogen atoms become aligned in a common direction. When submitted to pulses of radio waves, the energy content of the nuclei changes. After the pulse, a resonance wave is emitted when the hydrogen nuclei return to their previous state. The small differences in the oscillations of the nuclei are detected. (Animal magnetism?) Computer processing is used to build up a three-dimensional image that reflects the chemical structure of the tissue, including differences in the water content and in movements of the water molecules.

NMR is not just used to investigate biological samples, NMR techniques are used to map out the connectivity of the atoms as well as the 3-dimensional molecular structure and **stereochemistry** of the chemicals used in battery manufacture.

Damadian was the first to point out, in a landmark 1971 paper in *Science* (based on experiments involving lab rats), that MRI could be used to distinguish between healthy and cancerous tissue and in 1972 he filed the first patent for MRI scanning. Despite this, the Nobel Prize for Medicine inexplicably went to Dr Paul **Lauterbur** and Sir Peter **Mansfield** for their contributions to the development of MRI scanning.

1977 Engineers John **Birkner** and Hua-Thye **Chua** at Monolithic Memories Inc. invented a **programmable array logic (PAL)** chip. Now more commonly called a **PLD** or **programmable logic device**, it is a logic IC that can be programmed by the user. MMI's chip contained 2,048 tiny fuses in the interconnecting lines between the gates which could be blown to create almost any configuration of up to two hundred and fifty AND, OR, and NOT gates. Blowing the fuses is a relatively simple procedure that disconnects some gates while blowing the so called **"anti fuses"** make connections to others. PLD's are not re-programmable.

1978 The world's first **Compressed Air Energy Storage** **(CAES)** plant, a 290 MW unit belonging to E.N. Kraftwerke, built at Huntorf in Germany. The **pneumatic battery**

1978 Mechanically refuelable Metal-Air batteries proposed for electric vehicle propulsion by John F. **Cooper** and Ernest L. **Littauer** working at Lawrence Livermore Labs. **Aluminium Air** batteries were proposed as the most suitable cell chemistry. To date, metal-air batteries have not lived up to the promise claimed for them and several research programmes have been abandoned.

1978 Engineers at GCA (now defunct) invent the **Step and Repeat System** for exposing the photoresist on semiconductor wafers. Instead of using a single photomask for the whole surface of the wafer, a mask is made for a single integrated circuit. The devices on the wafer are then exposed one at a time with the wafer being moved to the next device between each exposure. The process is repeated until the pattern has been replicated across the entire wafer. The step and repeat process enabled major improvements in photolithography with increasing resolution and finer line-widths.

1978 "Speak and Spell" children's educational toy launched by TI. It included a 4-bit microcontroller, two 128-kbit ROMs and a speech synthesis chip and was the first use of the **digital signal processor (DSP)** concept in a commercial product. Using a method known as Linear-Predictive

Coding (LPC) more than 100 seconds of linguistic sounds could be stored in a highly compressed format in the 128 KB ROM chip which was very important in the days when ROM space was expensive. The speech synthesis chip allowed the basic sounds to be assembled into intelligent speech.

The original idea was proposed to a less than enthusiastic TI management in 1976 by Paul **Breedlove** and implemented by new recruit Richard **Wiggins** and senior designer Gene **Frantz**. Speak and Spell created a new market for a new type of device and DSP chips turned out to be one of TI's most successful products.

The modern DSP chip is a special-purpose CPU used for **digital signal processing** applications. It is a programmable device, with its own **native instruction code** typically providing ultra-fast instruction sequences, such as shift and add, and multiply and add, which are commonly used in math-intensive signal processing. Usually dedicated to a single task, they can be much faster than microprocessors which are designed to be general purpose devices. DSP chips are capable of carrying out millions of floating point operations per second.

They often include dedicated software such as mathematical transforms, for example, the **Fast Fourier Transform (FFT)** for carrying out special tasks. The first application of the FFT in a DSP was in the analysis of seismic data gathered in oil exploration tests. The FFT enabled the filtering of the desired signals from noise and interference in the seismic data. The effect of reverberations which masked returned signal could thus be removed from the signals reflected from rock strata. The FFT is now used in dozens of applications such as digital filtering, selective amplification of some frequencies and the suppression of others, audio and video signal compression and decompression, encryption and the analysis of complex signals into their spectral components.

Computerised axial tomography (CAT) is an example of DSP's used for image processing. X-rays from many directions are passed through the section of the patient's body being examined. Rather than creating a single photographic image, the DSP converts the detected x-ray signals into digital data which is used in combinations to create images which appear to be slices through the body showing much more detail than in a conventional exposure, allowing significantly better diagnosis and treatment.

DSP's are also widely used in a myriad of consumer products including cellphones, compact disks, sound cards, video phones, modems, hard disks and digital TVs.

1979 American researcher John B. **Goodenough** working at Oxford university perfects **Lithium-ion** rechargeable battery technology using Lithium Cobalt Oxide ($LiCoO_2$) and Lithium Manganese Dioxide ($LiMn_2O_4$) based cathodes but the patents for the invention were awarded to the UK Atomic Energy Commission (now AEA Technology) who funded the research. Sony of Japan however were the first to commercialise the technology. Goodenough did not benefit financially from the patents but in December 2000 he was awarded the Japan Prize (and $450,000) by The Science and Technology Foundation of Japan for his invention.

Subsequently working at the University of Texas in 1996, Goodenough patented the more stable Lithium Iron Phosphate ($LiFePO_4$) cathode chemistry.

1979 Dan **Bricklin** an MBA student at Harvard Business School conceived the idea of the **spreadsheet** and together with his friend Bob **Frankston** from MIT wrote **Visicalc**. Visicalc was the "killer application" which turned the personal computer from a curiosity into a necessity and rapidly became the indispensible tool for engineers, accountants and marketing planners worldwide. Unfortunately he did not patent the idea, being advised by his patent attorney that software was (at that time) difficult and costly ($10,000) to patent with the likelihood of success being only 10%. He thus missed out on reaping the full rewards of his innovative idea.

1980 Patents issued on the first **Zebra** Sodium/Nickel chloride cell. Originated in the mid 70's by the Council for Scientific and Industrial Research (CSIR) in South Africa, it was finally developed and patented by the UK Atomic Energy Authority in Harwell.

1980 The high power density, deep cycling **AGM (Absorbtive Glass Mat) Lead Acid battery** invented. It was introduced for military aircraft in 1985.

1980 The **Insulated Gate Bipolar Transistor (IGBT)** demonstrated by Indian born B. Jayant **Baliga** working at General Electric. It is a fast switching device capable of handling very high currents.

1980 American physicist, Carver **Mead** based at CalTech and transsexual computer scientist, refugee from an unsympathetic IBM, Lynn **Conway** co-authored the engineering textbook, **Introduction to VLSI Systems**, which quickly became the leading resource for designers of **Very Large Scale Integrated Ciruits**. Mead had predicted in 1972 that transistors could be made as small as 0.15 microns: - much, much smaller than the 10 micron state of the art technology at the time and he spent the intervening years developing the technology to achieve this submicron goal. Key to this was his development of the **silicon compiler**, a CAD application, analogous to a software compiler, which allowed the chip designer to specify the functions required on the chip in an easy to understand structured language. The resulting program was then translated by the computer into the tracks making up each layer of the silicon circuit and output to a high resolution plotter which provided the etching patterns for chip fabrication. This technology not only provided the necessary tools for a new generation of microprocessors and complex devices, it also encouraged the setting up of innovative **fabless semiconductor companies** supported by specialist **chip foundries**.

Conway, who was born and raised as a boy, did pioneering work on software design and computer architecture at IBM where he was known as Robert, however he was fired when he informed the company he was about to undergo a sex change operation. Continuing her career as Lynn Conway she was elected to the National Academy of Engineering and went on to be appointed Professor Emerita of Electrical Engineering and Computer Science at the University of Michigan.

1981 The **scanning tunneling microscope (STM)** was developed at IBM Zurich by German engineer Gerd **Binnig** and Swiss engineer Heinrich **Rohrer**. It does not give a direct image of an object like a true microscope does, but explores the structure of a surface by using a stylus that scans the surface at a fixed distance from it. It employs the principles of quantum mechanics and provides a higher resolution image than the SEM. Electrons form the tightly focused illuminating beam tunnel towards the surface of the sample and the current flow depends on the distance from the specimen. An image of the surface is constructed from the pattern of current flows. It is even possible to see, move and position individual atoms, which makes the scanning tunneling microscope an important tool in **nanotechnology**. (See also **Drexler** below)

See also **TEM** and **SEM**

Binnig an Rohrer shared half of the Nobel Prize in physics in 1986 for their achievement with Ernst **Ruska** who built the first electron microscope in 1932.

1981 Kim Eric **Drexler** at MIT in the USA published his paper on **nanotechnology** describing the physical principles of molecular manufacturing systems - Using **nanomachines** to make products with atomic precision.

1981 Paul **MacCready**'s Solar Challenger, the first **PV-powered airplane**, flies.

1982 Solar One, America's first commercial solar-thermal power plant opens in California demonstrating the feasibility of high power **solar generating systems**. More than 1,800 computer-controlled tracking mirrors reflect sunlight onto a 300-foot boiler tower, where steam is produced for generating 10 MegaWatts of electricity.

1982 Professor Kurt **Petersen** of Stanford University launched a new technology with his visionary publication, **"Silicon as a Mechanical Material"**, in which he proposed using semiconductor processing techniques and microelectronics materials to build microscopic mechanical and electromechanical components. It became the foundation of the **MEMS** and **NEMS** industries.

1983 The first computer with a user friendly **Graphical User Interface (GUI)**, the Apple "Lisa" was released by Steve **Jobs** from a project which owed many of its ideas to researchers at the Xerox PARC (Palo Alto Research Centre).

1984 Flash memory invented by Japanese Fujio **Masuoka** working for Toshiba in Japan. It is a form of **Electrically-Erasable Programmable Read-Only Memory (EEPROM)** that allows multiple memory locations to be erased or written in one programming operation. It uses **floating gate** construction and depends on **quantum tunneling** effects induced by relatively high voltages for both writing and erasing. Flash memory us commonly used in USB memory sticks.

1984 Xilinx co-founder Ross **Freeman** invents the **Field Programmable Gate Array (FPGA)** chip that can be customized by the user. It was a completely new form of user programmable logic in which the interconnections and hence the logic functions are defined by RAM cells. Typical logic elements include gates, flip flops and RAM lookup tables. Because the functionality is determined by the RAM, most FPGAs are re-programmable. FPGA's are ideal for building software defined products and for prototyping and low volume applications.

1985 Robert **Curl**, Harold **Kroto** and Richard **Smalley** by accident discovered a new class of Carbon molecules called **Buckminsterfullerenes** during an experiment to replicate the formation of long chain carbon atoms in the outer atmosphere of stars. They had set up an apparatus which vapourises graphite with a high power laser and allowed it to re-form in vacuum. To their surprise they discovered a new molecule consisting of 60 Carbon atoms. Carbon 60 is the third molecular form (**allotrope**) of carbon. Diamonds and graphite are the other two. It consists of 60 atoms of carbon arranged in hexagons and pentagons that resemble a soccer ball or a geodesic dome as designed by Buckminster Fuller.

Also called **Buckyballs** or **Fullerenes**, Buckminsterfullerenes are extraordinarily stable and impervious to radiation and chemical destruction. The

molecule is already finding experimental use in a wide variety of applications including **nanomaterials**, superconductors, lubricants, catalysts and electrodes in batteries and capacitors. See also **Buckytubes**
For this discovery the trio were awarded the Noble Prize for chemistry in 1996

1985 The first successful DIY **cordless power tool** the **"Twist"** screwdriver powered by a 2.4 Volt **NiCad** battery was introduced by **Skil** power tools, 24 years after the idea was pioneered by **Black & Decker**. Sadly nobody at Skil remembers the name of the employee whose idea did so much to boost the Skil brand name.

1980's Sealed Valve Regulated lead acid battery commercialised.

1986 The **Nickel-Metal Hydride** battery was patented by serial entrepreneur and inventor Stanford **Ovshinsky.**

1986 Gerd **Binnig** and Heinrich **Rohrer** working at IBM in Zurich develop the **Atomic Force Microscope** able not only to photograph individual atoms but to move individual atoms around.
The first practical **nanotechnology** tool.

1986 Hitachi built and tested a 5 MJ **Superconducting Magnetic Energy Storage** **(SMES)** evaluation system storing energy in the magnetic field of a large superconducting coil which was connected to the 6.6 kV power line. The **magnetic battery**.

1986 Johannes Georg **Bednorz** and Karl Alexander **Müller** at the IBM Research Laboratories in Zurich found a new family of **high temperature superconductors** **(HTS)**, based on ceramic materials which are normally insulators, whose critical temperature reaches 35 °K (-238 °C) and the following year further compounds with critical temperatures of 135 °K (-138 °C). The absence of electrical resistance at practical temperatures enables very high currents to be carried without loss opening up the possibility of a wider range of superconductor applications.

1986 Six Sigma quality standards, tools and techniques, a summary of developments in statistical quality control over the previous 50 years, was named and popularised by Motorola engineer Bill **Smith**. Six Sigma is actually a numerical measurement of quality. To achieve Six Sigma quality 99.99966% of what you do must be without defects. In other words it is a defect rate of just **3.4 parts per million (PPM)** products or parts made. Working to this standard raised the performance bar for western manufacturers, used to relatively lax AOQL tolerances, making quality **sampling plans** irrelevant.

The mathematics of Six Sigma were developed by **Gauss** who studied the **Normal Distribution**, represented by the **Bell Curve**, and defined the value of the **mean** and **standard deviation** which he called σ sigma. It is a characteristic of the normal probability distribution, also called the **Gaussian Distribution** that 99,99966% of all occurrences fall within plus or minus three standard deviations (3σ) from the mean, or that they have a spread of six standard deviations (6σ). The normal distribution can represent the probabilities of occurrences of random errors, or the spread of characteristics of certain populations. In manufacturing it can represent the frequency of occurrence of a characteristic, such as a dimension, a resistance value or a temperature, compared with its deviation from the norm or desired value, in other words the tolerance spread of the manufacturing output.

There's no magic to six sigma. The tolerance of the desired characteristic is set by the requirements of the design or the performance requirements of the product. Sigma is a measure of the variability of the output. Six sigma manufacturing simply means that the production process should be designed and controlled such that the six sigma spread of the desired output characteristics should be contained within the desired tolerance limits for the characteristic. The challenge comes in finding ways to achieve the reduced variability, or standard deviation, of the output.

1987 3D Systems launched **StereoLithography** with a machine they labeled the **SLA**-1 (StereoLithography Apparatus) enabling **Rapid Prototyping (RP)**. Plastic parts can be created directly from 3D CAD files by the electronic "slicing" of the 3D CAD file into a series of thin cross sections, translating the results into 2D position coordinates, and using these data to control placement of the "build" material. This process is repeated for each cross section and the object is built from the bottom up, one layer at a time. An SLA machine builds objects by directing uv light from a computer-controlled laser onto the surface of a vat of photosensitive liquid resin. When the light strikes the surface, the photopolymer solidifies. When one layer is completed, the part is lowered into the vat, a thin layer of new liquid spreads over the surface, and the process is repeated. Because each layer is as thin as 0.001in., objects can be made with very fine details. Used for **design verification** and **pattern making** before committing to expensive moulding tools.

1988 40MWH Lead Acid **load levelling battery** delivering 5000 Amps at 2000 Volts (10 MW) for 4 hours installed by Southern California Edison (SCE) at Chino in California.

1988 Electrical engineering professor Richard S **Muller** with colleagues **Fan** Long-Shen and **Tai** Yu-Chong at the University of California, Berkeley proposed a design for an electrostatic **micro-scale motor** fabricated from silicon. The following year they succeeded in producing the world's first operating **Micro-Electromechanical Systems (MEMS)**micro-motor. It was 100 microns across, or about the width of a human hair and was the first successful implementation of silicon micromachining technology first proposed in 1982 by **Petersen**.

1988 Albert **Fert** of the University of Paris-Sud and Peter **Grünberg** of the KFA research institute in Julich, Germany independently discovered that they could obtain a magnetoresistive effect many times greater than the previously known AMR (anisotropic magnetoresistance) effect discovered 130 years earlier by **Kelvin**. They consequently named it "**giant magnetoresistance**" or **GMR**.

The GMR device is constructed from an alternate stack of ferromagnetic (Fe, Co, Ni, and their alloys) and non-ferromagnetic (Cr, Cu, Ru, etc.) metallic layers each only a few atomic layers thick.

GMR replaced the AMR technology previously used for read-heads in magnetic disks and now also finds use in current sensors where it has better sensitivity and output signal level than Hall effect devices.

A GMR current sensor works as follows. A conductive non magnetic layer which carries the sensor current through the device is sandwiched between two layers of ferromagnetic materials whose magnetic moments face in opposite directions due to ferromagnetic coupling but at right angles to the sensor current path. The current to be measured flows through an external conductor which creates a local magnetic field into which the sensor is placed. When no current flows in the external circuit, no external magnetic field is present and the resistance of the sensor's non magnetic layer is very high so that the sensor current is very low. When an external magnetic field is present, due to current to be measured, the magnetic moments of the ferromagnetic materials both line up in the same direction as the external field, in parallel with the sensor current. This causes the resistance of the sensor current path to drop dramatically by as much as 50%.

1989 Martin **Fleischmann** of Southampton University and B. Stanley **Pons** of the University of Utah announced they had achieved **Cold Nuclear Fusion** using a beaker of heavy water containing two metal electrodes - one of platinum and one of palladium. It promised an unlimited source of cheap energy from a small portable power unit. Essentially an electrolysis system which produces more energy, in the form of heat, than it consumes, it was greeted with skepticism by the scientific community. Millions of pounds of research money were subsequently ploughed into further investigations in many countries of the world spawning over 3000 technical papers in the 1990's but despite the enormous investments and the continuing world-wide research effort, many researchers have been unable to replicate Pons and Fleischmann's results although some claimed to have succeeded. In 1993 technology licensing rights for the cold fusion system were sold by Utah University and in 1996 US patents on the technology were granted to a Dr James **Patterson** (see below). However, to this date, no practical cold fusion energy source has been produced as a result of all this activity. And incidentally, no energy has been produced by **hot nuclear fusion** either, despite heating suitable plasmas to 510 million degrees Celsius!!

Unfortunately there is no requirement to demonstrate a working model in order to receive a patent and people can apply for **patents** for things that don't yet work as many gullible investors have found to their cost.
Cold fusion has since entered the history books as a bad joke about bad science.

1989 US patent awarded to American physicist Paul M **Brown** for a **Betavoltaic battery** which provides **direct conversion** of nuclear energy into electricity. (Betavoltaic battery doesn't sound nearly as threatening as **Nuclear battery**, does it?).
Nuclear batteries were first demonstrated by **Ohmart** in 1951. During the 1950's nuclear batteries were developed by the US DOE and been in use by **NASA** since 1961. They were designed to meet the long life, high-voltage, high-current draw requirements of electrically powered space probes and satellites however the batteries used by NASA mainly use thermocouples to generate electricity indirectly by using the heat, rather than the nuclear radiation, emitted by radioactive **Plutonium-238**. In 1971 a patent was awarded to **Sampson** for the **Gamma Electric Cell** which converted the nuclear energy directly into electrical energy. The betavoltaic power cell is a similar device which captures the radiated energy in a semiconductor rather than in a dielectric material as in Sampson's cell. It contains mildly **radioactive isotopes** such as **Tritium**, an isotope of Hydrogen (Hydrogen-3), which emit only beta particles (electrons) as they decay and a **semiconductor** material which catches the beta particles as they are given off. The impact of the beta electron on the semiconductor P/N junction material causes a useable electric current to flow across the junction in some respects similar to a photovoltaic (solar) cell.
It is claimed that the cells can produce high voltages in the order KV but the energy density is low at only 24 W/Kg. The power output is therefore low, only tens of Watts and the technology is only suitable for low power applications. Tritium has a half life of 12.5 years and the useful battery life is thus claimed to be about 25 years. The cells never need recharging.
Betavoltaics came into the public eye when the public was already jaundiced by the **Cold Fusion** scandal. Concerns have been expressed about the technical feasibility of the conversion process and the use of radioactive materials in consumer products as well as the shielding and

containment they might require. (Small amounts of radioactive isotope **Americium-241** are in fact already used in consumer **smoke detectors** while other radioisotopes are used in a variety of medical, industrial and agricultural applications)

Currently (2004) low power hybrid betavoltaic batteries are being developed for use in mobile phones and laptop computers. Because the radiation source is not susceptible to conventional controls on the level of energy emitted, the betavoltaic cell in effect acts as a charger which provides a constant trickle charge to a standard **Lithium-Ion battery**. The fundamental concept of this controversial device however still remains unproven and no products have yet reached the market.

During the development Brown was subject to considerable ridicule and harassment including death threats. He was killed in a motor car accident in 2002 at the age of 47.

1989 Britain's National Power company starts work on a load levelling battery employing **Regenesys - Flow Battery** - technology. Initial project for TVA is a 12MW, 120MWh battery. (See Regenesys 2003 below)

1989 Development programme for **thin film batteries** led by John **Bates**, initiated at the US Oak Ridge National Laboratory (**ORNL**) in Tennessee. Batteries are built up from cell components which are printed in layers on to ceramic and other substrates using techniques originally pioneered in 1941 with **thick film circuits**.

1989 Engineers at Boeing claim to have achieved **photovoltaic cells** with a 37% conversion efficiency by stacking two layers of semiconductor material each optimised for a different wavelength (red and blue light). Very little has been heard of these high efficiency cells since then.

1989 British communications and computer engineer Timothy John **Berners-Lee**, working at CERN the European Particle Physics Laboratory in Geneva, invented a system for global information sharing based on **hypertext** which could use the **Internet** as a communications medium. His proposal included all the tools for implementing the system which he later called the **World Wide Web (WWW)**. He defined the language **HTML (HyperText Mark-up Language)** for specifying document layouts, **URLs (Universal Resource Locators)** to identify the location of each web page and **HTTP (HyperText Transfer Protocol)**, the set of rules for linking to pages on the Web. The following year he wrote the first **browser**, a text based method for retrieving and displaying the documents.
Berners-Lee's concept for the World Wide Web was made available royalty free to Internet users in 1991. His invention made it easy to store and retrieve information in an agreed common format and greatly simplified access to the Internet, taking it out of the universities and making it available to the public at large, not just to a few technical specialists.

The usage of the Web accelerated even more in 1993 when students at the US NCSA (National Center for Supercomputer Applications), Marc **Andreessen** aided by Eric **Bina**, introduced **NCSA Mosaic**, the first user friendly browser with a **Graphic User Interface (GUI)** and support for sound, video clips, forms, bookmarks, and history files.

When asked why he did not profit from the enormous potential of the WWW by patenting his ideas, Berners-Lee, who is committed to a global open system, commented - "Then there would have been a lot of little webs"

1990 Commercialisation of the **NiMH battery** after a relatively short period of development of only four years help[ed by the fact that the new NiMH cells could be made using the same equipment what had been used to manufacture NiCad cells.

1990 The first volume introduction of **Lithium secondary cells** for consumer applications after over ten years of development.

1990's New battery technologies enable the development of cordless and portable devices (power tools, mobile phones, lap-top computers, PDAs, digital cameras, personal care items) and consequently boost demand for batteries. Increased volumes bring prices down, reinforcing demand.

1991 Carbon nanotubes or **Buckytubes** discovered by the Japanese electron microscopist **Sumio Iijima** who was studying the material deposited on the cathode during the arc-evaporation synthesis of **fullerenes**. Buckytubes can exhibit either semiconducting or metallic properties. They also have the intrinsic characteristics desired in **nanomaterials** used as electrodes in batteries and capacitors, a tremendously high surface area (~1000 m^2/g), good electrical conductivity, and very importantly, their linear geometry makes their surface highly accessible to the electrolyte. Buckytubes have the highest reversible capacity of any carbon material for use in Lithium-Ion batteries.

1991 Swiss scientist Michael **Grätzel** and co-workers at the Swiss Federal Institute of Technology patent the **Grätzel solar cell** a regenerative battery depending for its operation on a photoelelectrochemical process similar to photosynthesis.

1992 Austrian born Karl **Kordesch** of Canada patents the reusable alkaline battery the so called **(RAM) Rechargeable Alkaline Manganese battery**. Kordesch holds 150 patents on battery and fuel cell technology.

1993 John **Cooper** working at the Lawrence Livermore Labs patents the **Zinc Air refuelable battery**, using a cell chemistry first demonstrated by **Heise** and **Schumacher** in 1932. The battery is charged with an alkaline electrolyte and zinc pellets which are consumed in the process to form zinc oxide and potassium zincate. Refueling takes about 10 minutes and involves draining and replacing the spent electrolyte and adding a new charge of zinc pellets. This short refueling times possible with mechanical charging are particularly attractive for EV applications. The spent electrolyte is recycled.

1994 Bellcore patent on **Plastic Lithium Ion (PLI)** technology granted. **Lithium polymer** cells with a **solid polymer electrolyte**. The **solid state battery**.

1994 Industry consortium set up by Mercedes Benz and MIT in the USA to define new set of automotive industry battery standards to address the problem of increasing demand for on-board electrical power. Currently there are over 50 industry members and the result has been the establishment of the **PowerNet 42V** standard based on a 36 Volt operating / 42 Volt charging battery. The operating voltage was chosen because it could conveniently be provided by three standard 12 Volt battery modules. Applications using this standard have been slow to materialise.

1995 Introduction of the **pouch cell** made possible by Lithium PLI technology.

1995 Duracell and Intel developed the **Smart Battery** system for **Intelligent Batteries** and proposed the specification with its associated **SMBus** as an industry standard.

1995 On-cell battery condition indicator or **fuel gauge** for consumer primary cells introduced by Energizer.

1995 English stuntman, swimming professional and inventor Trevor **Bayliss** devised a method of producing a practical long lasting supply of electricity from a wind up spring. Using springs to generate electricity is nothing new, but prior to Bayliss' invention, the energy tended to be produced for only a short duration. Bayliss devised a **clockwork battery** by connecting the spring through a gear box which released the energy slowly to a dynamo.

1995 BMW abandons **flywheel energy storage** after a test technician is killed and two others injured when the **containment** enclosure weighing 2000Kg failed to protect them from shrapnel when a high speed rotor failed. (See **Flywheels**)

1996 Dr James **Patterson,** a 74 year old American chemical engineer and inventor was awarded the first of eleven US patents on clean energy "Patterson Power Cells". Although his company Clean Energy Technologies Inc. (CETI) claims they are not based on **cold fusion** they use the discredited **Pons - Fleischmann** method of heating water by electrolysis, regarded by some skeptical scientists as a perpetual motion machine. So far, these amazing energy producing electrolysis cells have failed to displace batteries from the market.

1996 Researchers Theodore O. **Poehler** and Peter C. **Searson** at The Johns Hopkins University demonstrated an **all-plastic battery**, using doped polymer, polypyrrole (five membered ring structured organic molecule, capable of **redox reactions**) composite electrodes in place of the conventional electrode materials as well as conducting and insulating polymers for the electrolyte and the casing. The **composite electrodes** are made from polypyrrole-carbon fibre in which the **carbon fibres** act as an electrically conductive skeletal electrode for current collection. The battery generates 2.5 Volts, it is flexible and operates over a wide temperature range with a long cycle life, it can be made as thin as a credit card and is not detectible by conventional airport security devices. Despite claims that the cells are inexpensive and easy to manufacture, products using the technology have so far not appeared in the consumer marketplace.

1996 Solar-powered plane, the **Icare**, flew over Germany. Developed by Brauschweig University and the Stuttgart Academic Flying Group, it covered a distance of 350 kilometres, during a five hour flight. The wings and tail surfaces of the Icare are covered by 3000 super-efficient PV cells, with a total area of 21 m^2

1997 Annual shipments of **photovoltaic modules** reach 120 megawatts world wide.

1998 48MWH Sodium Sulphur **load levelling battery** delivering 6 MW for 8 hours installed by NGK for Tokyo Electric Power Company (TEPCO).

1998 CODATA readjusts the value of 300 **physical constants** reducing uncertainties to 20% or less of what they had been previously, except for the gravitational constant which was determined to be even more uncertain than previously measured.

2000 Dr Randell Lee **Mills**, a Harvard-trained medical doctor and chemist who also studied biotechnology and electrical engineering at MIT, proposed the **Hydrino Hydride Battery** for which he claimed a theoretical energy density of 10,000 Wh/Kg and a cell voltage of 70 Volts. This compares with 200 Wh/Kg and a cell voltage of 3.6 Volts for a Lithium-Ion battery. Its operation depends on a new phenomenon of quantum physics which Mills identified. Using a catalyst the orbiting electrons in a hydrogen atom can be persuaded to enter lower orbits (lower quantisation levels) than previously thought possible, forming new atoms which he called hydrinos and giving off huge amounts of energy in the form of ultra-violet light in the process. The hydrinos produced by this process have unique physical and chemical properties which make many new applications possible.

After the recent **cold fusion** débâcle you would think the scientific and investment community would be more cautious, yet Mills assembled a management board consisting of prominent captains of industry from the nuclear power and energy utilities, government advisors, academics and high ranking military officers all with experience in nuclear power and all with impeccable credentials. At the same time he raised $25 million of capital from electric utilities and venture funds and lined up Morgan Stanley Dean Witter to arrange an IPO (Initial Public Offering) for his company **BlackLight Power** Inc (BLP). Mills filed for several patents for his inventions and in 2000 he was granted a US patent for "Low Energy Hydrogen Methods and Structure" detailing the fundamental theory of his invention and 499 novell aspects of his work. Two days later, prompted by an outside inquiry, the patent office became concerned that the hydrino concept was "contrary to the known laws of physics and chemistry" and rejected the other patents which were in the pipeline including "Hydride Compounds" which had already been assigned a number and for which BLP had already paid the approval fee. BlackLight appealed, taking the issue to court but the appeal was rejected. There's still no word on the IPO and the scientific community hasn't yet produced any more hydrinos.

2000 Indian chemist Sukant K. **Tripathy** working at the University of Massachusetts demonstrates **polymer photovoltaic cells** for making **flexible solar panels** using nanotechnology. Unfortunately he did not live to see his dream of bringing low cost solar power to his native India since he was drowned at the age of 48 shortly after making the announcement however his technology was quickly adopted and is being commercialised by Nobel laureate Alan **Heeger**. Possible developments being pursued are photovoltaic fibres which can be woven into fabrics, particularly for military applications including tents and uniforms with the object of reducing the weight of batteries the soldier must carry around to power his electronic equipment. Ideal for the Indian army perhaps?

2000's Trends

- Environmental concerns and legislation creating a demand for "greener" energy which can be satisfied by wind, wave and solar power all of which use batteries for high power **load levelling**.
- The same drivers are also creating a demand for cleaner more efficient vehicles for which battery power is a cost effective solution.
- Smaller, lighter, lower cost batteries make **electric** and **hybrid electric vehicles** practical for the first time.
- Increasing use of electronics to get the best performance out of the battery.
- Cell manufacturing being concentrated in Asia with China taking a progressively higher share. Battery customisation remains close to the customer.
- Lithium technologies taking an increasing share of the market.
- **Fuel cells** used to power a variety of demonstrator vehicles. Still too expensive and complex for general adoption.

2001 John **Smalley** working at the U.S. Department of Energy's Brookhaven National Lab announced the development of **nanowires**, organic molecules called oligophenylenevinylene (OPV). These molecules are essentially "chains" of repeating links made up of carbon and hydrogen atoms arranged to promote strong, long-range electronic interactions through these molecules. They allow a very fast rate of electron transfer down the chain acting as extremely fine, low resistance wires only one molecule in diameter.

2002 Various patents filed on **nanomaterials** used in lithium and other batteries to achieve increases in charge and discharge rates of 10 to 100 times.

2002 Commercialisation of solid state Lithium polymer **thin film batteries** based on patents from **ORNL**.

2003 Teeters, Korzhova and **Fisher** working at the University of Tulsa in the USA patent the **nanobattery** so small that they can fit 60 of them across the width of a human hair. Through nanotechnology, objects are built in such a way that nearly every atom is precisely placed. Such a tiny battery could be used to drive a microbe-sized submarine through a patient's blood vessels.

2003 University of California, Berkeley, physics professor Alex **Zettl** created the first **nano-scale motor**, 15 years after Berkeley, engineers built the first **micro-scale motor**. The smallest motor made to date it is about 500 nanometers across, 300 times smaller than the diameter of a human hair, small enough to ride on the back of a virus. The first example of **nano-electromechanical systems (NEMS)**.

2003 University of California, San Diego, announced that they are developing something they call "**smart dust**." These are tiny **robots**, smaller than a grain of sand, powered by **nano batteries**, that could move through an artery, or through the air, or through contaminated water, to carry medication or sniff out hazardous materials.

2003 RWE the German multi utilities group, the new owners of National Power (now renamed to Innogy) pulled the plug on the **Regenesys** battery project before the battery was completed after it spent $250 Million over 14 years.

2003 The world's biggest battery was connected to provide emergency power to Fairbanks, Alaska's second-largest city. Without power lines between Alaska and the rest of the U.S., the state is an "electrical island." The $35 million rechargeable battery contains 13,760 large Nickel-Cadmium cells in 4 strings weighing a total of 1,300 tonnes and covering 2,000 square metres. The battery can provide 40 megawatts of power for up to seven minutes while diesel backup generators are started.

2003 Worldwide battery sales

- Total world sales value $48 billion.
- Sales value of small rechargeable batteries - $7.6 billion.
- More than 110 million automotive lead acid batteries were manufactured for more than 650 million vehicles on the world's roads. 81% of sales were to the replacement market.
- Sales value of industrial batteries for traction and standby power applications - $14 billion
- 500,000 electric bicycles per year sold in China.
- Unit sales of light electric vehicles (Bicycles, scooters, motorcycles and city runabouts) expected to be 10 million in 2004.

- The HEV/EV battery market is expected to grow at an AAGR of more than 50% to nearly $250 million in 2008.
- Total battery demand expected to exceed $60 billion by 2006 and $65 billion by 2008.

2003 Finnish metallurgist Rainer **Partanen** patents the **rechargeable aluminium air battery** using **nanotechnology** to achieve very high energy densities.

2004 Toshiba demonstrated a **direct methanol fuel cell** (DMFC) small enough to power mobile phones. The fuel cell provides an output of 100mW from a cell measuring 22x56x4.5mm. A single charge of 2cc of methanol will power an MP3 player for 20 hours.

2004 The transistor count on an a single **Intel Itanium2 microprocessor** chip was over 410 Million and the next generation is expected to exceed 1 Billion in 2005. It has a 128 bit system bus and an I/O bandwidth of 6.4 GB/sec. See also **Moore's Law** and **1952 transistor production** volume and **Intel 4004 microprocessor**.

2005 Korean bioengineer Ki Bang **Lee** working at Singapore's Institute of Bioengineering and Nanotechnology, developed a **paper battery** powered by **urine** for use as a simple, cheap and disposable power source for home health tests for diabetes and other ailments. It is composed of paper, soaked in copper chloride, sandwiched between layers of magnesium and copper and laminated in plastic. The test kit including the battery is about half the size of a credit card, 6cm by 3cm and 1mm thick. Typically the battery will provide around 1.5 Volts, with a maximum power output of 1.5 milliWatts with 0.2 millilitres of urine. A range of medical test kits incorporating biosensors or biochips is envisaged which use the body fluid being tested as the source of power and a variety of geometries and materials depending on the requirements of the test.

2005 Masaharu **Satoh** working at NEC in Japan reveals details of a high C rate **Organic Radical Battery (ORB)**. This is a low capacity battery which runs for only a short period but can be charged and discharged at 100C. It is small and light but delivers very high power for a short period making it ideal for UPS applications, particularly for laptop computers. According to NEC, a 1 WattHour battery can deliver 100 Watts and can be recharged in less than one minute. It uses a graphite cathode coated with a specially developed polymer material (2,2,6,6-tetramethylpiperidinoxy-4-yl methacrylate **PTMA** - the organic radical) which freely donates electrons to achieve the high current carrying capacity.

2005 Fraser **Armstrong** working at Oxford University demonstrated the prototype of a **biofuel cell** which uses as fuel the small amounts of free hydrogen available in the atmosphere and an enzyme to promote oxidation, rather than an expensive catalyst. It doesn't use a membrane to separate the reactants and is unaffected by carbon monoxide which poisons typical catalysts. Development is continuing.

2005 Chris **van Hoof** working at IMEC the Inter-university MicroElectronics Center at Leuven in Belgium demonstrated the latest version of his **thermo-electric generator** powered by body heat. Designed to be worn on the wrist, it uses 3500 Bismuth Telluride thermocouples generating a total of between 200 µWatts and 500 µWatts at up to 1.5 Volts intended for powering medical sensors.

2006 Researchers at MIT's Laboratory for Electromagnetic and Electronic Systems (LEES), John **Kassakian**, Joel **Schindall** and Riccardo **Signorelli** succeeded in growing **straight single wall nanotubes (SWNT)** with diameters varying from 0.7 to 2 nanometers and lengths of several tens of microns (one thirty-thousandth the diameter of a human hair and 100,000 times as long as they are wide) which they used to make

enhanced double layer capacitors with major performance improvements.

2007 Sony announces the **Sugar Battery**, a **Biofuel Cell** using glucose as its fuel with enzymes for catalysts, developed by Tsuyonobu **Hatazawa** working with Professor Kenji **Kano** from Kyoto University. It consists of an anode and a cathode separated by a proton-conducting membrane. A renewable fuel, such as a sugar, is oxidised by microorganisms at the anode, generating electrons and protons. The protons migrate through the membrane to the cathode while the electrons are transferred to the cathode by an external circuit. The electrons and protons combine with oxygen at the cathode to form water. It is expected to find use in medical applications.

2008 American inventor Lonnie **Johnson** discovered a breakthrough new method of turning heat into electrical energy which he used in the design of a new form of **thermoelectric battery**, details of which were published in the January issue of Popular Mechanics.
Called the **JTEC (Johnson Thermoelectric Energy Conversion) System**, it is an all solid-state heat engine using hydrogen as the working fluid circulating between two **Membrane-Electrode Assembly (MEA)** stacks, one hot, and one cold, operating on a thermodynamic cycle similar to the **Ericsson Cycle**. It depends on the electro-chemical potential of hydrogen pressure when applied across a **Proton Conductive Membrane (PCM)**. The MEA is similar to a fuel cell stack and consists of a membrane and a pair of electrodes. On the high-pressure side of the MEA, hydrogen gas is ionised **(oxidised)** releasing protons and electrons. The pressure differential across the stack forces protons through the membrane while the electrons flow through an external load. On the low pressure side, the protons are **reduced** by the electrons to reform hydrogen gas.
If current is passed through the MEA a low-pressure gas can be "pumped" to a higher pressure.
The cycle needs an electrical jolt to start the proton flow. The resulting pressure differential produces voltage across each of the MEA stacks. The higher voltage at the high-temperature stack forces the low-temperature stack to pump hydrogen from low pressure to high pressure, maintaining the pressure differential.

The system can be compared to a gas turbine engine, the low temperature MEA stack is equivalent to the compressor stage and the high temperature MEA is the power stage.
The available energy is equal to the difference between the energy produced by the high pressure stack and the energy consumed by the low pressure stack. The larger the temperature differential between the stacks the higher the efficiency. Johnson claims he can achieve conversion efficiencies of over 60 percent.

There has been very little news about the device since the initial announcement, nor have any new practical products been seen.

2009 What have you got in mind? Give us a call - We'd like to help you. admin@woodbank.com

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A

AC Inverter - An electrical circuit which generates a sine-wave output (regulated and without breaks) using the DC current supplied by the rectifier-charger or the battery. The primary elements of the inverter are the DC/AC converter, a regulation system and an output filter.

A/D Converter (ADC) Analogue/Digital Converter. A device which converts continuously varying analogue signals into a binary coded digital form.

Acid - A proton donor. A compound containing hydrogen which dissociates in aqueous solution producing positively charged hydrogen ions (H^+). An acidic solution has a pH less than 7.0

Active material - The chemically reactive materials in an energy cell which react with each other converting from one chemical composition to another while generating electrical energy or accepting electric current from an external circuit.

Ageing - Permanent loss of capacity with frequent use or the passage of time due to unwanted irreversible chemical reactions in the cell.

AGM (Absorbtive Glass Mat) battery - A lead acid battery using a glass mat to promote recombination of the gases produced by the charging process.

Alkali - A compound which dissolves in water producing negatively charged hydroxide ions. Alkaline solutions are strongly basic and neutralise acids forming a salt and water.

Alkaline battery - A battery which uses an aqueous alkaline solution for its electrolyte.

Ambient temperature - The average temperature surrounding the battery, typically air.

Amorphous - Without definite shape or structure, without crystalline structure.

Ampere (Amp) - The unit of current flow equal to one coulomb per second.

Ampere hours (Ah) - The unit of measure used for comparing the capacity or energy content of a batteries with the same output voltage. For automotive (Lead Acid) batteries the SAE defines the Amphour capacity as the current delivered for a period of 20 hours until the cell voltage drops to 1.75 V.

Strictly - One Ampere hour is the charge transferred by one amp flowing for one hour. 1Ah = 3600 Coulombs.

Ampoule battery - A battery in which the electrolyte is stored in a separate chamber from the cell electrodes until the battery is needed.

Analogue (Analog) circuit - An electronic circuit in which an electrical value (usually voltage or current, but sometimes frequency, phase) represents something in the physical world.The magnitude of the electrical value varies with with the intensity of an external physical quantity.

Also - An electrical circuit which provides a continuous quantitative output (as opposed to a digital output which may be a series of pulses or numbers) in response to its input.

Anechoic chamber - A room whose walls do not reflect either electromagnetic or acoustic waves.

Anion - Particles in the electrolyte of a galvanic cell carrying a negative charge and moving toward the anode during operation of the cell.

Anisotropic - Showing differences of property or of effect in different directions.

Anode - The electrode in an electrochemical cell where oxidation takes place, releasing electrons. During discharge the negative electrode of the cell is the anode. During charge the situation reverses and the positive electrode of the cell is the anode.

ANSI - The American National Standards Institute publish standards for batteries jointly with NEMA. (See below)

Aqueous solution - Chemical components in liquid or gel form.

Arrhenius Equation - The relationship between the rate at which a chemical reaction proceeds and its temperature. In general terms, heat speeds up the chemical action.

Assembled battery - A battery composed of two or more cells.

Atomic Number - Specific to individual elements - represents the number of electrons in the atom.

Auger analysis - Similar to ESCA but does not provide information on the chemical state (oxidation etc.) of the elements.

Authentication - Verification that an item is from an approved source and/or that it is able to meet its declared specification.

B

Base - A proton acceptor. A compound containing hydrogen which dissociates in aqueous solution producing negatively charged hydroxide (OH^-) or other ions. Alkalis are bases and a basic solution has a pH greater than 7.0

Battery - Two or more electrochemical energy cells connected together to provide electrical energy.

Battery Management System (BMS) - Electronic circuits designed to monitor the battery and keep it within its specified operating conditions and to protect it from abuse during both charging and discharging.

Battery Monitoring - Sometimes confused with BMS of which it is an essential part, these circuits monitor the key operating parameters (current, voltage, temperature, SOC, etc.) of the battery and provide information to the user.

Bobbin - A cylindrical cell design utilizing an internal cylindrical electrode and an external electrode arranged as a sleeve inside the cell container.

Bootstrap - To do something seemingly impossible using only the available resources. In the context of DC battery power circuits it means generating a DC voltage higher than the battery voltage.

British Thermal Units (BTU) - A unit of heat energy defined as the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit. One Btu is equal to about 252 calories, or 778 foot pounds, or 1.055 kilojoules or 0.293 watt hours.

Buck regulator - A switching regulator which incorporates a step down DC-DC converter. A transformerless design in which the lower output voltage is achieved by chopping the input voltage with a series connected switch (transistor) which applies pulses to an averaging inductor and capacitor.

Butler Volmer equation - Used by cell designers to predict the current which will flow in a battery. It is the sum of the anodic and cathodic contributions and is directly proportional to the surface area of the electrodes, increasing exponentially with temperature.

Button cell - Miniature cylindrical cell with a characteristic disc shape.

C

C Programming Language - The preferred programming language for embedded software used in many battery management applications. Robust, fast and powerful, it allows low level access to information and commands while still retaining the portability and syntax of a high level language.

C Rate - C is a value which expresses the rated current capacity of a cell or battery. A cell discharging at the C rate will deliver its nominal rated capacity for 1 hour. Charging and discharging currents are generally expressed as multiples of C. The time to discharge a battery is inversely proportional to the discharge rate.

- NC is a charge or discharge rate which is N times the rated current capacity of the battery where N is a number (fraction or multiple)
- C_N is the battery capacity in AmpHours which corresponds to complete discharge of the battery in N hours (N is usually a subscript). Also written as the N-Hour rate.

Calendar life - The expected life time duration of a cell whether it is active use or in storage

CAN Bus - Controller Area Network The automotive industry standard for on-board vehicle communications. It is a two wire, serial communications bus which is used for networking intelligent sensors and actuators

Calorimeter - A device or chamber for measuring the heat generated by objects placed inside it.

Capacitance (C) - A measure of the ability of a device to store charge per unit of voltage applied across the device. C=Q/V Farads.

The current through the capacitor is given by the relationship i =C $^{d}/_{dt}$V(t)

Capacitor - A passive electrical device that stores energy in an electric field.

Capacity - The electric energy content of a battery expressed in "Watt hours". Batteries with the same output voltage also use "Ampere hours" for comparing capacities.

Capacity offset - A correction factor applied to the rating of a battery if discharged under different C-rates from the one rated.

Catalyst - A chemical agent which promotes or influences a chemical reaction without itself being permanently changed by the reaction. Used in recombinant cells and fuel cells

Cathode - The electrode in an electrochemical cell where reduction takes place, gaining electrons. During discharge the positive electrode of the cell is the cathode. During charge the situation reverses and the negative electrode of the cell is the cathode.

Cation - Particles in the electrolyte of a galvanic cell carrying a positive charge and moving towards the cathode during operation of the cell.

CCA - Cold Cranking Amperes - A measure used to specify the cold cranking capability of automotive SLI batteries. For Lead Acid batteries it is the constant current a battery can deliver during a continuous discharge over a period of 30 seconds at -18°C without the terminal voltage dropping below a minimum of 1.2 Volts/cell.

CE - The CE marking indicates that the product has been designed and manufactured in conformity with the essential requirements of all relevant EU directives, and submitted to the relevant conformity assessment procedure.

Cell -A closed electrochemical power source. The minimum unit of a battery.

Cell balancing - The process used during charging to ensure that every cell is charged to the same state of charge. Also called "Equalisation".

Cell chemistry - The active materials used in the energy cell.

Cell reversal - A condition which may occur multi cell series chains in which an over discharge of the battery can cause one or more cells to become completely discharged. The subsequent volt drop across the discharged cell effectively reverses its normal polarity.

Charge - The process of replenishing or replacing the electrical charge in a rechargeable cell or battery.

Charge acceptance - The ability of a secondary cell to convert the active material to a dischargeable form. A charge acceptance of 90% means that only 90% of the energy can become available for useful output. Also called Coulombic Efficiency or Charge Efficiency. See alternative definition below.

Charge carriers - The particle carrying the electrical charge during the flow of electrical current . In metallic conductors the charge carriers are electrons , while ions carry the charges in electrolyte solutions .

Charge efficiency - The ratio (expressed as a percentage) between the energy removed from a battery during discharge compared with the energy used during charging to restore the original capacity. Also called the Coulombic Efficiency or Charge Acceptance. See alternative definition above.

Charge pump - A power supply which uses capacitors instead of inductors to store and transfer energy to the output. A voltage doubler or tripler.

Charge rate - The current at which a cell or battery is charged. Generally expressed as a function of rated capacity C.

Charge retention - The ability of a battery to retain its charge in zero current conditions. Charge retention is much poorer at high temperatures. See also Self Discharge

Charge, state of - The available or remaining capacity of a battery expressed as a percentage of the rated capacity.

Charge transport - The movement of electrical charge from one part of the system to another, occurring through the **drift** of ions under the influence of electrical potential difference. Also called **Electromigration**.

CID Circuit Interrupt Device - A small mechanical switch which interrupts the current through an energy cell if the internal pressure exceeds a predetrmined limit. Usually applied in small cells only.

Coin cell - Small cylindrical cell with a disc shape.

Conditioning - Cycle charging and discharging to ensure that formation (see below) is complete when a cell enters service or returns to service after a period of inactivity

Conductance - Strictly speaking the Conductance applies to resistive circuits and is the reciprocal of the Resistance. Battery manufacturers have their own definition which applies to the frequency dependent elements of the circuit, that is - C=I/E where C is the conductance, I is the test current applied to a component (the cell) and E is the in phase component of the ac voltage E producing it.(Compare with Ohm's Law R=E/I)

Measuring the conductance of a battery gives a good indication of its state of health.

Conducting polymer - Plastic materials which have some of the properties of metals. Used as solid electrolytes in batteries. Also used in the construction of fuel cell membranes, capacitor electrodes and in applications requiring anti-static plastics. (See also Polymer below)

Constant current charge CC - A charging scheme which maintains the current through the cell at a constant value.

Constant voltage charge CV - A charging scheme which maintains the voltage across the battery terminals at a constant value.

Contacts - The battery output terminals.

Conversion Efficiency - The percentage of the input energy of a process that is converted to energy of the desired type.

Coulomb - A unit of electric charge. One coulomb (1C) is equal to the charge transferred by a current of one ampere in one second.

Coulomb Counting - A method of determining the state of charge of a battery by integrating the ingoing and outgoing discharge currents of a battery over time.

Coulombic Efficiency - The ratio (expressed as a percentage) between the energy removed from a battery during discharge compared with the energy used during charging to restore the original capacity. Also called Charge Efficiency or Charge Acceptance.

Coup de fouet (Whiplash) - A dramatic initial voltage drop when a battery is suddenly called upon to supply a heavy load. The voltage recovers after a short time once the electro-chemical discharge process stabilises.

Critical Temperature (Superconductor) **-** The temperature below which a superconducting material must be cooled in order to exhibit the property of superconductivity.(See below)

CSA - The Canadian Standards Association is a not-for-profit membership-based association serving business, industry, government and consumers in Canada and the global marketplace.

Curie point or **Curie temperature** - The temperature above which a ferromagnets and some other materials undergo a sharp change in their magnetic properties losing their ability to possess a net spontaneous or remanent magnetization in the absence of an external magnetic field.

Current limit - The maximum current drain under which the particular battery will perform adequately under a continuous drain.

Current shunt - A current shunt is an low value resistance, whose value is accurately known, placed in series between the battery and the load. The voltage drop across the shunt is used to determine the value of the current using Ohm's Law. Used in series, it is not a shunt in the literal sence of the word. Its name derives from the fact that early ammeters could not handle high currents and the shunt was used to bypass most of the current around the meter.

Cut-off voltage - The specified voltage at which the discharge of a cell is considered complete. See also End voltage and Termination voltage

CVT - Constant Voltage Transformer

Cycle - A single charge and discharge of a battery.

Cycle life - The number of cycles a battery can perform before its nominal capacity falls below 80% of its initial rated capacity. See also Float life below.

Cylindrical cell - A cell in which the electrodes are rolled up in a spiral and placed into a cylindrical container.

D

D/A Converter (DAC) Digital/Analogue Converter - A device which converts a digitally coded signal into an equivalent analogue signal.

DC-DC Converter - An electronic circuit which takes a DC input voltage and converts it to a different, desired DC output voltage.

Deep cycle battery - A battery designed to be discharged to below 80% Depth of Discharge. Used in marine, traction and EV applications.

Deep discharge - Discharge of at least 80% of the rated capacity of a battery.

Delta V - The voltage drop which occurs in some cells, notably NiCads, which indicates that the cell is fully charged.

Dendritic growth - The formation from small crystals in the electrolyte of tree like structures which degrade the performance of the cell.

Depth of discharge DOD - The ratio of the quantity of electricity or charge removed from a cell on discharge to its rated capacity.

Diamagnetism - The property of a substance which is repelled instead of attracted by a magnet. A diamagnetic material will be repelled from a magnet no matter what pole it is near. It is exhibited by all common materials, but is very weak and often swamped by stronger paramagnetic or ferromagnetic effects. Metals such as bismuth, copper, gold, silver and lead, as well as many nonmetals such as graphite, water and most organic compounds are diamagnetic. See also Ferromagnetism and Paramagnetism.

Dielectric - A nonconductor of electricity, such as an insulator, or a substance in which an electric field can be maintained with a minimum loss of power. The material used between two conducting plates to form a capacitor.

Dielectric Constant - Used to determine the ability of an insulator to store electrical energy. The dielectric constant is the ratio of the capacitance induced by two metallic plates with an insulator between them to the capacitance of the same plates with air or a vacuum between them.

Discharge - The change from chemical energy within the cell into electrical energy to operate a external circuit.

Discharge capacity - The amount of energy taken from the battery when discharged at the rated current and ambient temperature until the discharge end voltage is reached. Generally expressed in units of Watt hours (or Ampere hours for batteries with the same voltage).

Discharge rate - The current delivered by the cell during discharging. Expressed in Amperes or multiples of the C rate.

Discharge voltage - The voltage between the terminals of a cell or battery under load, during discharge.

DOD - Depth of Discharge (see above)

Dropout - In a voltage regulator, the lower limit of the AC input voltage where the power supply just begins to experience insufficient input to maintain regulation. The dropout voltage for linears is quite load dependent. For most switchers it is largely design dependent, and to a smaller degree load dependent.

Dry Cell - A Leclanché cell with a gel electrolyte.

DST - Dynamic Stress Test. Accelerated battery life tests specified by the USABC. Cycling down to 80% DOD twice per day at different temperatures.

Duty Cycle - The load current or power a battery is expected to supply for specified time periods.

dT/dt - The rate of change of temperature with time. The rapid rate of temperature rise is used to detect the end of the charging cycle in NiMH batteries.

E

ECE-15 - The United Nations Economic Commission for Europe specification for urban driving cycle simulation.

E Rate - Discharge or charge power, in watts, expressed as a multiple of the rated capacity of a cell or battery which is expressed in watt-hours. For example, the E/10 rate for a cell or battery rated at 23.4 watt-hours is 2.34 watts. (This is similar to the method for calculating C-Rate.)

Elastomer - elastic or plastic materials that resemble rubber which resume their original shape when a deforming force is removed.

Electret - The electrostatic equivalent of the permanent magnet. Dielectric materials that have been permanently electrically charged or polarised.

Electrochemical equivalent - The weight of a substance which is deposited by the passage of one coulomb of current.

Electrode - Conducting element within a cell in which an electrochemical reaction occurs.

Electrode potential - The voltage developed by a single electrode, determined by its propensity to gain or lose electrons.

Electrolysis - Chemical modifications, oxidation and reduction produced by passing an electric current through an electrolyte.

Electrolyte - A substance which dissociates into ions (charged particles) when in aqueous solution or molten form and is thus able to conduct electricity. It is the medium which transports the ions carrying the charge between the electrodes during the electrochemical reaction in a battery.

Electromotive Force EMF - The ability of an electrical source to deliver energy. It is the difference of potentials which exists between the two electrodes of opposite polarity in an electrochemical cell. Also known as the **Cell voltage**.

Embedded System - A special-purpose computer system, which is completely encapsulated within the device it controls, usually performing a limited range of specific pre-determined tasks. This allows the use of simpler or cheaper dedicated microprocessors providing only the minimum functionality required by the application, or alternatively the entire processing power of the microprocessor can be focused on a single task. Battery Management Systems will normally be implemented with an embedded system.

EMC - Electromagnetic compatibility (EMC) is the ability of electronic and electrical equipment and systems to operate without adversely affecting other electrical or electronic equipment or being affected by other sources of electromagnetic interference.

End voltage - The prescribed voltage that indicates that the discharge is complete. (see also Cut-off voltage)

Endothermic - Describes a chemical action in which heat is absorbed.

Energy Content - The absolute amount of energy stored in a battery expressed in Wh or Joules

Energy density - The amount of energy stored in a battery. It is expressed as the amount of energy stored per unit volume or per unit weight (Wh/L or Wh/kg).

Enthalpy - The amount of energy released or absorbed by a chemical reaction. The "Free Enthalpy" (also called the " Change in Gibbs Free Energy") in a reaction is the maximum amount of chemical energy available from a system that can be converted into electrical or mechanical energy and vice versa. (discharge and charge respectively)

Entropy - A measure of the disorder of a system. Used as a measure of heat content.

EPROM - Electronically Erasable Programmable Read-Only Memory. Re-writable memory that does not lose data if power is lost to the system (non-volatile). Available in three types:

- **OTP** One Time Programmable non-erasable.

- **Windowed** (ultraviolet light erasable) used for prototyping and development work.
- **EEPROM** Electronically Erasable Programmable Read-Only memory.

Equalisation - The process of bringing every cell in a battery chain to the same state of charge (SOC)

ESCA - Electron Spectroscopy for Chemical Analysis. Equipment using x-ray irradiation to identify the presence of individual chemical elements particularly for surface coatings and thin films where it can be used for selected element depth profiling. A machine typically costs about $750,000

ESD - Electrostatic Discharge

EUDC - Extra Urban Driving Cycle. European additional specification for urban driving cycle simulation.

EUROBAT - The Association of European Storage Battery Manufacturers. (Mainly Lead acid)

Eutectic - A mixture in such proportions that the melting-point is as low as possible, the constituents melting simultaneously.

EV - Electric Vehicle

Exercise - Commonly describes the discharging to one volt per cell and subsequent charging. Used to maintain or condition NiCad and NiMH cells.

Exothermic - Describes a chemical action in which heat is produced.

F

Faraday Cage - An enclosure with no apertures (holes, slits, windows or doors) made of a perfectly conducting material. No electric fields are produced within the Faraday cage by the incidence of external fields upon it or by currents flowing on the perfect conductor such that the perfectly conducting enclosure is a perfect electromagnetic shield.

Fast charge - Charging in less than one hour at about 1.0C rate. Needs special charger.

FCC - The Federal Communications Commission is an independent United States government agency charged with regulating interstate and international communications by radio, television, wire, satellite and cable.

Ferromagnetism - The property of a substance which is attracted to a magnet. Iron, cobalt, nickel, gadolinium, dysprosium and alloys containing these elements are ferromagnetic. See also Diamagnetism and Paramagnetism.

FET - Field Effect Transistor - A semiconductor device designed for fast, current switching applications.

Firmware - Instructions programmed into a micro-controller that controls its operation. A combination of hardware and software.

FlexRay Bus - A fault tolerant, high speed data communications bus designed for complex automotive control applications.

Float charge - An arrangement in which the battery and the load are permanently connected in parallel across the DC charging source, so that the battery will supply power to the load if the charger fails. Compensates for the self-discharge of the battery.

Float life - The expected lifetime in hours of a battery when used in a float charge application. See also Cycle life above.

Flooded Lead Acid cell -In "flooded" batteries, the oxygen created at the positive electrode is released from the cell and vented into the atmosphere. Similarly, the hydrogen created at the negative electrode is also vented into the atmosphere. This can cause an explosive atmosphere in an unventilated battery room. Furthermore the venting of the gasses causes a net loss of water from the cell. This lost water needs to be periodically replaced. Flooded batteries must be vented to prevent excess pressure from the build up of these gasses. See also Sealed Lead

Acid (SLA) Cells which overcome these problems.

Flow battery - A battery in which the electrolyte flows or is pumped through the electrodes

Flywheel battery - A flywheel stores kinetic energy in a high speed (up to 100,000 rpm) rotating cylinder and is "charged" and "discharged" via an integral motor/generator. High power availability but low capacity.

Formation - Electrochemical processing of a cell electrode(or plate) between manufacturing and first discharge, which transforms the active material into its useable form.

FPGA - Field Programmable Gate Array. A microchip which can be made with thousands of programmable logic gates. Often used for prototype or custom designs, they permit short development times and low production costs.

FUDS - Federal Urban Driving Schedule specification for urban driving cycle simulation.

Fuel Cell - An electrochemical generator in which the reactants are stored externally and may be supplied continuously to a cell.

Fuel Gauge - An indication of the State of Charge (SOC) or how much charge is remaining in a battery. Also called a Gas Gauge.

Fuzzy Logic - A method of deriving precise answers from vague data.

G

Galvanic cell - An electrolytic cell in which chemical energy is converted to electrical energy on demand

Gas chromatography - The separation and identification of individual chemical components from a sample. A typical machine costs over $250,000..

Gas gauge - An electrical circuit which indicates the amount of charge remaining in a battery.

Gassing - The generation of a gaseous product at one or both electrodes as a result of the electrochemical action. In Lead Acid batteries gassing produces hydrogen and oxygen.

Gel cell - A battery which uses gelled electrolyte, an aqueous electrolyte that has been fixed by the addition of a gelling agent.

Gibbs Free Energy - See **Enthalpy**

GMR (Giant MagnetoResistance) A spintronic effect that produces a large change in resistance of the conducting layers that occurs when thin stacked layers of ferromagnetic and nonmagnetic materials are exposed to a magnetic field. "Giant" refers to its very large electrical signal. The technology is used to manufacture current and magnetic sensors.

Gravimetric Energy Density (WhKg) - The energy output per unit weight of a battery.

Gravimetric Power Density (W/Kg) - The power output per unit weight of a battery.

Ground loop - An unintentionally induced feedback loop or crosstalk caused by two or more circuits sharing a common electrical ground.

H

Half Cell Reaction - The electrochemical reaction between the electrode and the electrolyte.

Hall effect - When a conductor carrying an electric current is placed in an external magnetic field perpendicular to the current there is voltage drop across the conductor at right angles to the current which is proportional to the magnetic field. Used to measure magnetic field strength.

Hertz - The standard unit of frequency of one cycle per second.

HEV - Hybrid Electric Vehicle (See below)

Hibernation state - A state in which the the status of the various functions of a circuit has been saved in memory and the circuit has been switched off save energy. When power is reapplied, data taken from the memory is used to restore the circuit to the status it had before switch off. (See also "Standby state" below)

High rate discharge - Discharge at a current of 2C or more.

Horse Power (Hp) - The rate of doing work. 1 Hp = 746 Watts or 550 foot pounds per second.

Hybrid Electric Vehicle (HEV) - A vehicle which has two forms of motive power one of which is electric.

Hydrometer - A device used for measuring the specific gravity of a fluid. In the case of lead acid batteries the specific gravity provides a measure of the state of charge of the cell.

Hygrometer - An instrument for measuring humidity. Often confused with a hydrometer.

Hysteresis - A property of physical and chemical systems that do not instantly follow the forces applied to them, but react slowly, or do not return completely to their original state. In the case of magnetic systems, when an external magnetic field is applied to a magnetic material, the material becomes magnetised absorbing some of the external field. When the external field is removed the material remains magnetised to some extent, retaining some magnetic field. See also hysteresis in batteries.

I

IEC - The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes international standards for all electrical, electronic and related technologies.

IGBT - Insulated Gate Bipolar Transistor. It has the output switching and conduction characteristics of a bipolar power transistor but is voltage controlled like the MOSFET giving the high current carrying capability of the bipolar transistor but the ease of control of the MOSFET.

Immobilised electrolyte - A construction technique used in lead-acid batteries. The electrolyte (the acid) is held in place against the plates instead of being a free-flowing liquid. The two most common techniques are Gel Cell and Absorbed Glass Mat.

Impedance - A measure of the response of an electric circuit to an electric current. The actual value is frequency dependent. The current is opposed by the capacitance, inductance and resistance of the circuit.

Impedance testing - Determination of the battery's internal impedance by measuring the voltage drop across a cell when it carries a sample alternating current.

Inductance (L) - A measure of the ability of a device to store magnetic flux per unit of rate of change of current passing through the device. Measured in Henries.

The voltage across the inductor is given by the relationship $v = -L \, {}^{d}/_{dt} I(t)$

Inductive charging - A charger in which the charging current is induced by an external induction coil into a secondary transformer winding housed within the battery together with rectifying and charge control circuits.

Inductor - A passive electrical device that stores energy in a magnetic field

Infra red radiation - The spectrum of the heat radiated by a warm body.

Inhibitor - A substance added to the electrolyte to prevent or slow down an unwanted electrochemical process. Used to prevent corrosion of the electrodes or the formation of dendrites.

Insert mouldings - Plastic parts containing metal inserts used to simplify product assembly and reduce costs. Inserts made from metal or other materials are placed in the mould prior to the injection of plastic. The plastic flows around the inserts and fixes their position.

Intelligent battery - Battery containing circuitry enabling some communication between the battery and the application or with the charger.

Intelligent charger - Charger which is able to react to inputs from an intelligent battery to control or optimise the charging process.

Intelligent Energy Manager IEM - A system for reducing the demands that power hungry applications place on the battery.

Intercalation - This insertion of ions into the crystalline lattice of a host electrode without changing its crystal structure.

Internal impedance - Resistance to the flow of AC current within a cell. It takes into account the capacitive effect of the plates forming the electrodes.

Internal resistance - Resistance to the flow of DC electric current within a cell, causing a voltage drop across the cell in closed circuit proportional to the current drain from the cell. A low internal impedance is usually required for a high rate cell.

Inverter - An electrical circuit which generates a sine-wave output (regulated and without breaks) using the DC current supplied by the rectifier-charger or the battery. The primary elements of the inverter are the DC/AC converter, a regulation system and an output filter.

Ion - An atom or group of atoms which is electrically charged. Depending on how they were created - through release or absorption of electrons - ions can be either positively charged (**Cations**) or negatively charged (**Anions**).

IP Code - Ingress Protection Rating. It consists of the letters IP followed by two digits. The first digit represents the degree of protection against dust and solids. The second digit represents the degree of protection against moisture and water.

IR drop - The voltage drop across a battery due to its internal impedance. See also Ohmic loss below.

I^2R loss - The energy generated or lost as heat due to the internal resistance of the battery. Also known as the Joule heating effect.

ISO - A network of national standards institutes from 148 countries working in partnership with international organizations, governments, industry, business and consumer representatives.

Isotope - Atoms of the same element with the same atomic number (the same number of protons) but with different numbers of neutrons an hence different weights.

J

Josephson effect - The flow of electric current through nonconductive material when placed between two superconductors. Used to detect very weak magnetic fields.

Joule - "J" A measure of work, energy or cell capacity. For electrical energy, one Joule is one Amp at one Volt for one Second, or one

WattSecond. 1 Wh = 3.6kJ. For mechanical energy one Joule is a force of one Newton acting over one metre i.e. One newton metre.

Joule heating - The I^2R loss or heating effect of a current **I** flowing through a resistance **R**.

K

Kalman Filter - A mathematical technique for deriving accurate information from inaccurate data.

Kelvin Bridge - An electrical circuit for measuring very low impedances such as battery internal impedance, contact resistance and resistance of circuit elements such as wires and cables. Also known as the Kelvin Connection for voltage sensing.

Keyed connectors - Plug and socket pairs with a unique mechanical profile which can only be mated with eachother in a particular orientation and which do not allow mating with connectors of a different design.

L

LDO (Low Drop Out) Regulator - An LDO is a type of linear regulator. Dropout voltage is the minimum input to output voltage differential required for the regulator to sustain an output voltage within 100mV of its nominal value.

Leakage - The escape of electrolyte to the outer surface of the battery or cell.

Leclanché Cell - A zinc carbon or zinc chloride cell.

Lifetime Energy Throughput - The total amount of energy in Watthours which can be taken out of a rechargeable battery over all the cycles in its lifetime before its capacity reduces to 80% of its initial capacity when new.

LIN Bus - Local Interconnect Network An automotive industry standard for on-board vehicle communications. It is a single wire, serial communications bus which is used for networking intelligent sensors and actuators

Linear charger - Charger which uses a series regulator. The simplest and cheapest type but less efficient than a Switch mode charger.

Linear Regulator - A linear, or Series, regulator is a voltage regulator which uses a transistor or FET in series with the load, operating in its linear region, to subtract excess voltage from the applied input voltage, producing a regulated output voltage.

Lithium Ion Cell - A secondary lithium cell in which both the negative and positive electrodes are lithium insertion (intercalation) compounds. Also known as rocking chair, shuttlecock or swing cell.

Lithium Polymer Cell - A lithium ion cell with a solid polymer electrolyte.

Load current - The discharge current provided by a battery, or drawn by a battery powered device.

M

Magnetic Resonance Imaging (MRI) - A method of looking inside the human body without using surgery, harmful dyes or x-rays based on Nuclear Magnetic Resonance (NMR).

Magnetohydrodynamic Generator MHD - The production of electricity by passing a conducting fluid or plasma through a magnetic field.

Mass spectrometer - A device which produces a mass spectrum of a sample to find out its composition by ionising the sample and separating ions of differing masses and recording their relative abundance by measuring intensities of ion flux. Mass spectroscopy allows detection of compounds by separating ions by their unique mass. A typical machine costs around $250,000

Memory effect - Reversible, progressive capacity loss in nickel based batteries found in NiCad and to a lesser extent in NiMH batteries. It is caused by a change in crystalline formation from the desirable small size to a large size which occurs when the cell is recharged before it is fully discharged.

Mechanical charging - Charging by replacing one or more of the active chemicals in the cell.

Meissner effect - When a superconducting material is cooled below its critical temperature it will exclude or repel a magnetic field. A magnet moving by a conductor induces currents in the conductor. This is the principle upon which the electric generator operates. But, in a superconductor the induced currents exactly mirror the field that would have otherwise penetrated the superconducting material causing the magnetic field to be excluded and magnet to be repulsed. This phenomenon is known as diamagnetism (see above) and is so strong that a magnet can actually be levitated over a superconductive material.

Metal hydride - A metallic compound which is able to absorb hydrogen. Used as the negative electrode (anode) of a Nickel Metal Hydride battery.

Microcycles - Rapid, shallow charge and discharge cycles which occur in automotive battery applications, particularly those which involve regenerative braking.

MISRA - Motor Industry Software Reliability Association.

Monomer - A small molecule that may become chemically bonded to other monomers to form a polymer. From Greek mono "one" and meros "part".

Morphology - The microstructure of the solid phases of materials. The grain shapes and structure of crystals of the chemical components of a battery.

MOSFET - A Field Effect Transistor made using Metal Oxide Semiconductor technology. Controlled by voltage rather than current like a bipolar transistor. MOSFET's have a significantly higher switching speed than bipolar power transistors. Suitable for high power circuits, they generate almost no loss (little heat generation), enabling fast response, excellent linearity, and high efficiency. The positive temperature coefficient inhibits thermal runaway. (Degrades to an SFET - Smoke and Fire Emitting Transistor if subject to excessive voltages). See also IGBT.

MSDS - Material Safety Data Sheet. Information provided by battery or cell manufacturers about any hazardous materials used in their products.

Multiplexer - A multiplexer is a device which enables several communications links or signals to share a single communications channel. At the receiving end of the link a demultiplexer separates the signals again. Various coding schemes are possible which enable the signals to be transmitted simultaneously or sequentially.

N

Nano - From the latin word meaning "dwarf". One billionth or 10^{-9}. One micron = 1000 nanometers. One nanometer is about the diameter of 3 to 6 atoms (depending on the element).

Nanotechnology - Nanomaterials (nanocrystalline materials) are materials possessing grain sizes on the order of a billionth of a meter. Used for electrodes and separator plates in NiMH and Lithium ion batteries and also in supercapacitors. Their foam-like (aerogel) structure provides a very large effective surface area which can hold considerably more energy than their conventional counterparts.

Nanobattery - Very small battery built using nano technology. Of microscopic size 1 micron diameter they deliver 3.5 volts. The electrodes are ceramic or carbon particles and the electrolyte is a solid polymer impregnated in an aluminium oxide membrane.

Negative Delta V (NDV) - The NDV is the drop in the battery voltage which occurs when NiCad or NiMH cells reaches their fully charge state. Used to detect the end of the charging cycle in Nicads.

Negative electrode - The electrode which has a negative potential. The anode.

NEMA - The National Electric Manufacturers Association in the USA publish standards for batteries jointly with ANSI. (See above)

Nernst equation - Used by cell designers to calculate the voltage of a chemical cell from the standard electrode potentials, the temperature and to the concentrations of the reactants and products.

Neural Network - A powerful data modeling tool that is able to capture and represent complex input/output relationships. It is used as a basis for self learning systems.

Nominal capacity - Used to indicate the average capacity of a battery. It is the average capacity when batteries are discharged at 0.2C within one hour of being charged for 16 hours at 0.1C and 20± 5°C. (or discharge at 0.05C for automotive batteries - SAE) Definition depends on the conditions. See Ampere Hours Ah above

Nominal voltage - Used to indicate the voltage of a battery. Since most discharge curves are neither linear nor flat, a typical value is generally taken which is close to the voltage during actual use.

NRE - Non-Recurring Engineering costs. A one time charge for design and implementation of custom battery packs or other products.

NTC - A thermistor with a negative temperature coefficient, whose resistance decreases with increasing temperature.

Nuclear fission - Occurs when the atomic nucleus splits into two or more smaller nuclei plus some by-products. These by-products include free neutrons and photons (usually gamma rays). Fission releases substantial amounts of energy (the nuclear binding energy). The neutrons released by the fission process may collide with other nuclei causing them in turn to undergo fission initiating to a chain reaction.

Nuclear fusion - A process in which two nuclei join together to form a larger nucleus and releasing energy. It takes considerable energy to overcome the repulsion between the two positively charged nuclei to force them to fuse. The fusion of lighter nuclei, which creates a heavier nucleus and a free neutron, will generally release even more energy than it took to force them together. It is an exothermic process which could produce self-sustaining reactions.

Nuclear Magnetic Resonance (NMR) - The interaction of atomic nuclei placed in an external magnetic field with an applied electromagnetic field oscillating at a particular frequency . Magnetic conditions within the material are measured by monitoring the radiation absorbed and emitted by the atomic nuclei. Used in MRI scanners and as a spectroscopy technique to obtain physical, chemical, and electronic properties of molecules.

O

OEM Original Equipment Manufacturer - A company with the prime responsibility for conceiving, designing, manufacturing and distributing a particular product line.

Ohmic loss - The voltage drop across the cell during passage of current due to the internal resistance of the cell. Also known as IR loss or IR drop.

Open circuit voltage OCV - The voltage of a cell or battery with no load attached measured with a voltmeter at room temperature.

Operating voltage - Voltage between the two terminals of the battery with a load connected.

Operational amplifier (Op amp) - A high gain DC amplifier with a voltage gain of 100 to 100,000 or more and a very high (ideally infinite) input impedance and very low (ideally zero) output impedance. Op-amps are the basic building block of linear integrated circuits used for analogue circuit applications. They have positive and negative inputs which allow circuits which use feedback to achieve a wide range of functions.

Opportunity charging - Intermittent charging from sources whenever or wherever power is available.

Opto-isolator - Also called **opto-coupler**. An isolation device using optical techniques (an LED transmitting across a small gap to a photocell) to isolate the electrical connections between a transmitter and a receiver. Used to pass signals between high voltage and low voltage circuits and to replace switches and relays. Having no electrical connection they also help to cut down on ground loops.

Osmosis - The diffusion of a solvent through a semi permeable membrane from a region of low solute concentration to a region of high solute concentration. The semi permeable membrane is permeable to the solvent, but not to the solute, resulting in a chemical potential difference across the membrane which drives the diffusion. The solvent flows from the side of the membrane where the solution is weakest to the side where it is strongest to equalise the concentration on both sides.

Over-charge - Continuous charging of the battery after it reaches full charge. Generally overcharging will have a harmful influence on the performance of the battery which could lead to unsafe conditions. It should therefore be avoided.

Over-current - Exceeding the manufacturer's recommended maximum discharge current for a cell or battery.

Over-discharge - Discharging a battery below the end voltage or cut-off voltage specified for the battery.

Overmoulding - An injection moulding technique used to encapsulate and protect components or small sub-assemblies, usually by moulding a soft, flexible plastic over the components which must be able to withstand the temperatures and pressures of the moulding process. Used for cable connectors, gaskets, and for incorporating small components into cables. Two shot moulds may be used to provide soft plastic grips over a hard plastic shell.

Over-voltage - The difference between the actual potential at which an electrochemical reaction occurs, and its theoretical equilibrium potential.

Oxidation - The loss of electrons by a chemical species

P

Packaging - In a battery, the mechanical structure used to contain and protect its components (cells, electronic circuits, contacts etc.).

Parallel connection - Connection together of the cell terminals of the same polarity of two or more cells to form a battery of higher capacity.

Paramagnetism - The property of a substance which is attracted to a magnet. It is similar to ferromagnetism except that the attraction is weaker. When a paramagnetic material is placed in a strong magnetic field, it becomes a magnet as long as the strong magnetic field is present. But when the strong magnetic field is removed the magnetic effect is lost. Below the substance's Curie temperature a paramagnetic material becomes ferromagnetic. Paramagnetism is exhibited by materials containing transition elements, rare earth elements and actinide elements. Liquid oxygen and aluminium are also examples of paramagnetic materials. See also Diamagnetism and Ferromagnetism.

Passivation layer - A resistive layer that forms on the electrodes in some cells after prolonged storage impeding the chemical reaction. This barrier must be removed to enable proper operation of the cell. Applying charge/discharge cycles often helps in preparing the battery for use. In other applications, passivation is used as a method of shielding a metal surface from attack.

Periodic Table of Elements - A tabular display of the known chemical elements. The elements are arranged by electron structure so that many chemical properties vary regularly appearing in groups with common properties across the table. Each element is listed by its atomic number and chemical symbol .

Permanent charge - The charging current which can safely be continuously supported by the battery, regardless of the state of the charge.

Peukert's equation An empirical formula that approximates how the available capacity of a battery changes according to the rate of discharge. The equation shows that at higher currents, there is less available energy in the battery.

Peukert number A value that indicates how well a battery performs under heavy currents. A value close to 1 indicates that the battery performs well; the higher the number, the more capacity is lost when the battery is discharged at high currents. The Peukert number of a battery is determined empirically.

pH - (potential (of) hydrogen) is a logarithmic measure of the concentration of hydrogen ions (H^+) in a solution and, therefore, its acidity or alkalinity (basicity). **pH = -log[H +]**

The "pH" scale extends from 0 to 14 (in aqueous solutions at room temperature). A pH value of 7 indicates a neutral (neither acidic nor basic) solution. A pH value of less than 7 indicates an acidic solution, the acidity increases with decreasing pH value. A pH value of more than 7 indicates an alkaline or basic solution, the alkalinity or basicity increases with increasing pH value.

Photovoltaic cell - A device that directly converts the energy in light into electrical energy. Also called a photocell, a solar cell or a PV cell.

Photovoltaic effect - The generation of an electromotive force as a consequence of the absorption of radiation. In practice a current which flows across the junction of two dissimilar materials when light falls upon it.

Pilot Cell - A selected cell whose condition is assumed to indicate the condition of the entire battery.

Plates - The electrodes used in a flat plate cell.

PNGV - **P**artnership for a **N**ew **G**eneration of **V**ehicles. A partnership between government, industry and academia in the USA to improve all aspects of automotive design in which batteries figure highly.

Polarisation - The change in the potential of a cell or electrode from its equilibrium value caused by the passage of an electric current through it. There are two irreversible electrochemical components, the "electrode polarisation" at the electrodes and the "concentration polarisation" in the electrolytic phase plus an ohmic loss component due to the electrical resistance of the cell. Also due to the build up of gas bubbles on the electrodes.

Polarity reversal - Reversal of the polarity of a battery or cell due to over discharge.

Polymer - Strictly it is a substance made of long repeating chains of molecules called monomers which may be identical or different. The term polymer is often used in place of plastic, rubber or elastomer. In battery technology "polymer" usually refers to a solid (plastic) ionic conductor that is an electrical insulator but passes ions. (See also Conducting Polymer above)

Polyswitch - A resettable fuse. (See below)

Positive electrode - The electrode which has a positive potential. The cathode. Electric current from this electrode flows into the external circuit.

Pouch cell - A battery or cell contained in a flexible metal foil pouch.

Power density - The amount of power available from a battery. It is expressed as the power available per unit volume or per unit weight (W/L or W/kg).

PowerNet - The standard proposed for next generation of automotive batteries. Nominally 42 Volt systems.

Power transistor - A high current, bipolar transistor controlled by the current through the gate. Used in linear (series) regulators as the voltage dropper between the unregulated voltage input and the regulated output. Also used as a high current switching device in control and protection circuits. Needs a high current to turn it on and is slow to turn off and its negative temperature coefficient makes it prone to thermal runaway. For these reasons it was mostly superceded by MOSFETs in high power battery switching applications. See also Thyristor and IGBT.

ppm - Parts Per Million

Primary battery - A battery that is non-rechargeable.

Prismatic cell - A slim rectangular sealed cell in a metal case. The positive and negative plates are stacked usually in a rectangular shape rather than rolled in a spiral as done in a cylindrical cell.

Progressive dies - Multi-stage stamping tools for producing complex metal components from flat metal strip in a hydraulic or eccentric press. The die consists of two or more stages each of which carries out punching, drawing or folding operations with each down stroke of the press. Between each stroke, the strip moves from stage to stage through the die. Complex profiles and three dimensional shapes can be built up from a series of simpler operations which take place progressively at each stage as the strip passes through the die.

Protection - A facility incorporated into battery packs to protect the cells from out of tolerance working conditions or misuse.

PTC - A thermistor with a positive temperature coefficient, whose resistance increases with temperature.

PPTC - A Polymeric Positive Temperature Coefficient device. It is a non-linear thermistor, more commonly called a resettable fuse.

Pulse charger - Versatile, hybrid charger having some of the advantages of both switch-mode and linear chargers. More costly than both.

Pulse discharge - A high rate discharge, usually of 1 second or less.

Q

Quick charge - Charging in three to six hours at about 0.3C rate. Needs special charger.

Quiescent current - The current which continues to be drawn from the battery when the application it powers is in standby or hibernation mode.

R

Ragone Plot - The graphical illustration of the specific energy of a cell as a function of its specific power.

RAM cells - Rechargeable Alkaline Manganese cells.

RAPS - Remote-Area Power Supplies - Power systems deriving their energy from local solar or wind sources using a battery for energy storage and supplying the load through DC-DC converters or AC inverters.

Rate - When applied to cells it usually means the cells current carrying capacity.

Rated capacity - The specified capacity of a battery.

Reconditioning - One or more deep discharges below 1.0 V/cell with a very low controlled current, causing a change to the molecular structure of the cell and a rebuilding of its chemical composition. Reconditioning helps break down large crystals to a more desirable small size, often restoring the battery to its full capacity. Applies to nickel-based batteries. See also refurbishment (below)

Recombinant system - Sealed secondary cells in which gaseous products of the electrochemical charging cycle are made to recombine to recover the active chemicals. A closed cycle system preventing loss of active chemicals. Used in Nicads and SLA batteries.

Recovery - The lowering of the polarization of a cell during rest periods.

Recycling - Reclamation of materials without endangering human health and the environment.

Redox - A contraction of the words "reduction" and "oxidation". The two chemical reactions on which cell chemistries depend.

Redox Battery - A battery in which the chemical energy is stored in two dissolved ionic reactants separated by a membrane.

Reduction - The gain of electrons by a chemical species.

Refurbishing - The repair of worn out or damaged batteries. This is not the same as reconditioning (see above).

Regenerative braking - This uses the electrical drive motor in an electric vehicle to act as a generator returning energy to the battery when overdriven mechanically by the vehicle wheels. This provides a powerful braking effect and at the same time captures energy which would otherwise be wasted or dissipated in the brakes.

Regenesys - A high power Sodium Polysulfide Bromine "Flow Battery".

Regulator - See Voltage regulator.

Resealable safety vent - The resealable vent internal to a cell to release excessive internal pressure**.**

Relay - A mechanical switch operated by a solenoid.

Reserve battery - Batteries which are stored in an inactive state without their electrolyte. They are only activated when needed by the introduction of the electrolyte. See also Water-activated batteries and Ampoule batteries.

Reserve capacity - The number of minutes at which the battery can be discharged at 25 Amps and maintain a terminal voltage higher than 1.75 volts per cell, on a new, fully charged battery at 80degrees Fahrenheit(27C). Defines a battery's ability to power a vehicle with an inoperative alternator or fan belt. Used for comparing automotive SLI batteries.

Resettable fuse - A fuse which protects against excessive current and temperature by interrupting the flow of current. After opening it will reset after the fault conditions have been removed but only after it has cooled. It requires no manual resetting or replacement. The "Polyswitch" is an example of this.

Resistance welding - Resistance welding is a process used to join metallic parts with electric current. There are several forms of resistance welding, including spot welding, seam welding, projection welding, and butt welding.

Rest periods - Interruptions to the charging process to allow the chemical reactions in the battery to stabilise.

Reversible reaction - A chemical reaction which can be reversed to reconstitute the original components.

RFI - Radio Frequency Interference. Transmitted/emitted RFI affects other external equipment. Susceptibility measures the immunity of equipment from received RFI. See also EMC

RFID - Radio Frequency Identification. Small tags incorporating a radio transmitter which can be used to identify or track items of value.

Rocking Chair Cell- A lithium ion cell

RS232 connection - A standard for serial transmission of data between two devices.

RS485 connection - A standard for serial transmission of data between multiple devices.

S

SAE - Society of Automotive Engineers. The SAE Technical Standards Board issues and recommends industry standards.

Safety vent - A safety mechanism that is activated when the internal gas pressure rises above a normal level.

Sampling Rate - The repetition frequency at which digital samples are taken of an analogue quantity.

Sealed cells - A cell which remains closed and does not release gas or liquid when operated within the limits of charge and temperature specified by the manufacturer. An essential component in recombinant cells.

Secondary battery - A battery which can be recharged and used repeatedly.

Self-discharge - Capacity loss during storage due to the internal current leakage between the positive and negative plates.

SEM (Scanning Electron Microscope) - Apparatus used to investigate the physical structure of cell components and surfaces. They typically cost about $500,000 or more.

Semiconductor - An insulator whose conductivity can be manipulated by the addition of impurities (doping), by introduction of an electric field, by exposure to light , or by other means.

Separator - A film or grid to separate 2 electrodes to prevent short-circuiting and retain electrolyte.

Series connection - The connection of positive to negative of two or more cells to form a battery of higher voltage.

Series regulator - Another name for a Linear regulator

Service life - The period of useful life of a battery before a predetermined end point is reached.

Shedding - The loss of material from the plates of Lead Acid batteries.

Shelf life - The duration a cell can be kept in storage and still retain its ability to give a specified performance. See also Battery Storage

Shrouded terminals - Terminals surrounded by an insulating shroud which prevents accidental contact with the terminal.

Shunt - A device which allows electric current to pass around another point in the circuit.

Shunt regulator - A voltage regulator which uses a transistor or FET, in parallel with the load, which shorts out the excess voltage when the applied input voltage exceeds a specified limit producing a regulated output voltage. It is a simple but lossy design.

Shuttlecock cell - A lithium ion cell.

Sintering - Heating a mixture of powdered metals, sometimes under pressure, to the melting-point of the metal in the mixture which has the lowest melting-point, the melted metal binding together the harder particles.

SLA Battery - Sealed Lead Acid battery. In sealed batteries the generated oxygen combines chemically with the lead and then the hydrogen at the negative electrode, and then again with reactive agents in the electrolyte, to recreate water. A recombinant system. The net result is no significant loss of water from the cell. See also Flooded Lead Acid cell.

SLA - Equipment used for rapid prototyping. See StereoLithography Apparatus below.

SLI Battery - Common automotive battery used for Starting Lighting and Ignition

Slow charge - Charging overnight in 14 to 16 hours at about 0.1C rate. Safe and simple.

Smart Battery - An intelligent battery which contains information about its specification, its status and its usage profile which can be read by its charger or the application in which it is used.

SMBus - System Management Bus. A two wire, 100 KHz, serial bus for interconnecting Smart Batteries which have built in intelligence, with their associated chargers or applications.

Solar cell - A photovoltaic cell. Solar cells convert sunlight energy into electric current. They do not store energy.

Solar panel - An array of photocells providing an increased output.

Solenoid - A coil containing an iron plunger which moves when a current is passed through the coil.

Solid State Battery - Cells with solid electrolytes. Lithium polymer cells are examples of this technology

SOC - State of Charge. See below.

SOH - State of Health. See below.

Specific Energy - Same as Gravimetric Energy Density (Wh/Kg)

Specific Gravity SG - The ratio of the weight of a solution compared with the weight of an equal volume of water at a specified temperature. It is used to determine the charge condition in lead acid batteries.

Specific Power - Same as Gravimetric Power Density (W/Kg)

Spintronics - A technology used in solid state devices which exploits the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge. Also known as magnetoelectronics.

Spiral Wound - Battery construction in which the electrodes with the electrolyte and separator between them are rolled into a spiral like a jelly roll (Swiss roll).

Stacked Electrodes -

Standard charge - The normal C/10 charge used to recharge a cell or battery in 10 hours. Other definitions (charging periods) also apply.

Standby power - A fully charged battery ready to take over supplying a load in case of emergency.

Standby state - A state in which the main functions of a circuit have been powered down to save energy, but power remains applied to the circuit ready to make a rapid restart. (See also "Hibernation state" above)

State of Charge- SOC - The available capacity of a battery expressed as a percentage of its rated capacity.

State of Health- SOH - A measurement that reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery. It takes into account such factors as charge acceptance, internal resistance, voltage and self-discharge. It is not as precise as the SOC determination.

Stereolithography (SLA) - A Rapid Prototyping (RP) system for creating plastic parts directly from 3D CAD files. The RP model speeds design validation and is also finds use as a master pattern.

Stoichiometry - The branch of chemistry that deals with the numerical proportions in which substances react.

Storage life - The length of time a cell or battery can be stored on open circuit without permanent deterioration of its performance. See also Battery Storage

Studs - Threaded bolt connectors used on high power cells

Sulphation - Growth of lead sulphate crystals in Lead-Acid batteries which inhibits current flow. Sulphation is caused by storage at low state of charge.

Supercapacitor - A capacitor that can store a large amount of energy. Also called Ultracapacitor or Booster capacitor.

Superconductivity - A phenomenon occurring below a very low, characteristic critical temperature in certain materials (superconductors), characterised by the complete absence of electrical resistance and the damping of the interior magnetic field (the Meissner effect). Superconductors can carry currents that will not decay.

Swelling - Distortion of cells caused by expansion of the active chemicals due to temperature and pressure effects.

Swing cell - A lithium ion cell

Switcher - A switch mode regulator.

Switch mode charger - Charger which uses a switch mode regulator. More efficient but more costly than a Linear charger.

Switch mode regulator - A switching regulator is a voltage regulator which uses an output stage, switched repetitively on and off, together with energy storage components (capacitors and inductors) to generate a DC output voltage. Regulation is achieved through Pulse Width Modulation (PWM). Output voltages can be generated that are greater than or less than the input voltage, and multiple output voltages can be generated with a single regulator.

T

Tabs - Flat connectors used on pouch cells.

Tafel equation - The relationship between the internal electrode potentials in a battery and the current which flows. This is an exponential relationship based on empirical results which quantifies the elecrochemical reactions. It is analogous to the Arrhenius equation which quantifies the thermochemical process relating the temperature to the rate at which a chemical action progresses.

Taper charge - In quick chargers the charging current is is progressively reduced in a controlled way by controlling the supply voltage. In slow chargers the voltage is fixed and the charging current reduces in an uncontrolled way due to increase in the cell voltage as the charge builds up.

Temperature cut-off - A temperature sensing method which detects heat rise in a cell at overcharge and switches the charger off or to a lower rate of charge.

Temperature sensor - An electronic device which provides a voltage analogue of the temperature of the surface on which it is mounted. A thermistor is an example.

Termination voltage - The maximum voltage which can be tolerated by a cell during charging without damaging the cell. The cell voltage at which the charging process should be terminated.

Thermal Capacity - The amount of energy required to raise the temperature of an object by one degree Celsius. Expressed in Joules/Kg.

Thermal fuse - A safety device which interrupts a circuit when it detects excessive temperature.

Thermal imaging - A photographic technique which displays the range of temperatures of a warm body in the form of a colour spectrum. Used as a design verification tool for detecting hot spots in battery and other equipment designs.

Thermal management - The means by which a battery is maintained within its operating temperature limits during charging and discharging.

Thermal runaway - A condition in which an electrochemical cell will overheat and destroy itself through internal heat generation. This may be caused by overcharge or high current discharge and other abusive conditions.

Thermistor - An electrical device whose resistance varies with temperature. They are used as temperature-measuring devices or in electrical circuits to compensate for temperature variations of other components.

Thyristor - Also called a **Silicon-Controlled Rectifier** or **SCR**, it is a solid-state high current semiconductor switching device similar to a diode, with an extra terminal which is used to turn it on. Once turned on, the thyristor will remain on (conducting) as long as there is a significant current flowing through it. If the current falls to zero, the device switches off. See also Power transistor.

Traction battery - A high power deep cycle secondary battery designed to power electric vehicles or heavy mobile equipment.

Transient response - The ability of an electrical or other device to respond faithfully to sudden changes to the input conditions.

Trickle charge - A continuous charge at low rate, balancing losses through local action and/or periodic discharge, to maintain a cell or battery in a fully charged condition. Normally at a C/20 to C/30 rate.

TÜV - TÜV Rheinland Group (TUV - Technical Inspection Association) is an international service company which documents the safety and quality of new and existing products, systems and services.

U

UL - Underwriters Laboratories Inc - (UL) is an independent, not-for-profit product safety testing and certification organization based in the USA. UL marking indicates that the product conforms with the safety standards laid down by Underwriters Laboratories.

Ultracapacitor - See "Supercapacitor" above.

Ultrasonic welding - Ultrasonic welding involves the use of high frequency sound energy to soften or melt the thermoplastic at the joint. Parts to be joined are held together under pressure and are then subjected to ultrasonic vibrations usually at a frequency of 20, 30 or 40kHz.

UPS - Uninterruptible Power Supply

USABC - The United States Advanced Battery Consortium

V

Valence - The combining capacity of an atom expressed as the number of single bonds the atom can form or the number of electrons an element gives up or accepts when reacting to form a compound.

Venting - The release of excessive internal pressure from a cell in a manner intended by design to preclude explosion.

Voltage cutoff - A voltage sensing device which will end a charge or discharge at a preset voltage value.

Voltage limit - A voltage value a battery is not permitted to rise above on charge and/or fall below on discharge

Voltage regulator - A circuit which provides a fixed or controlled voltage output from a variable voltage input. Used in power supplies and chargers. Switching regulators , Linear regulators and Shunt regulators are the most common types.

Voltaic efficiency - The ratio (expressed as a percentage) between the voltage necessary to charge a secondary cell and the corresponding discharge voltage.

Volumetric Energy Density (Wh/L) - The energy output per unit volume of a battery

Volumetric Power Density (W/L) -The power output per unit volume of a battery

VRLA battery - Valve Regulated Lead Acid Battery

W

Ward-Leonard controller - A motor-generator system which uses a AC motor driving a variable voltage DC generator which drives a DC motor to provide a variable power transmission. Used for high power load testing.

Watt - A unit of power, the rate of doing work. Watts = Amps X Volts = One Joule per second.

WattHours Wh - A measure of the capacity of a battery. The amount of work done in one hour.

1 Wh = 3.6 kJ.

Well to wheel efficiency - The ratio between the mechanical energy ultimately delivered to the road wheels of a vehicle and the chemical energy content of the oil consumed in providing it. It is used to compare the fuel efficiencies of different methods of powering road vehicles and takes into account the refining process, the energy loss in the distribution process (in the case of hydrogen, the energy used to compress it) and the conversion efficiency of the vehicle's power unit.

Wet Cell - A cell with free flowing liquid electrolyte.

X

X-ray Crystallography - The use of the property of X-ray diffraction by crystals to determine their physical structure.

Y

Z

Zapping - A desperation measure to revive a shorted cell suffering from dendrites. A very high current, low voltage pulse from a large capacitor used in an attempt to vaporise the dendrites.

Zebra battery - A high temperature Sodium Nickel Chloride battery delivering high power.

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Rechargeable Lithium Batteries

Characteristics

Lithium is the lightest of metals and it floats on water. It also has the greatest electrochemical potential which makes it one of the most reactive of metals. These properties give Lithium the potential to achieve very high energy and power densities in high power battery applications such as automotive and standby power.

Many variations of the basic Lithium chemistry have been developed to optimise the cells for specific applications or perhaps in some cases to get around the patents on the original technology. Lithium metal reacts violently with water and can ignite into flame. Early commercial cells with metallic lithium cathodes were considered unsafe in certain circumstances, however modern cells don't use free Lithium but instead the Lithium is combined with other elements into more benign compounds which do not react with water.

The typical Lithium-ion cells use Carbon for its anode and Lithium Cobalt dioxide or a Lithium Manganese compound as the cathode. The electrolyte is usually based on a Lithium salt in an organic solvent.

Lithium batteries have now taken their place as the rechargeable battery of choice for portable consumer electronics equipment. Though they were expensive when introduced, volume production has brought the prices down.

See more details below.

History

Advantages

In many ways Lithium is almost the perfect cell chemistry and many variants exist. Practical Lithium based rechargeable batteries were first demonstrated in the 1970's, and they are now used in very high volumes in low power applications such as mobile phones, laptops, cameras and other consumer electronic products. They have many attractive performance advantages which make them also ideal for higher power applications such as automotive and standby power.

- High cell voltage of 3.6 Volts means fewer cells and associated connections and electronics are needed for high voltage batteries. (One Lithium cell can replace three NiCad or NiMH cells which have a cell voltage of only 1.2 Volts)

- No liquid electrolyte means they are immune from leaking.
- Very high energy density (About 4 times better than Lead acid). For example a 3.5 ton electric powered LDV light van uses 750Kg of Lead acid batteries. The same capacity could be provided by less than 200 Kg of Lithium batteries, allowing the van an increased payload of half a ton. Alternatively. The van's range of only 50 miles could be quadrupled by using the same weight of Lithium batteries.
- Very high power density. As above.
- Very small batteries also available. Solid state chemistry can be printed on to ceramic or flexible substrates to form thin film batteries with unique properties.
- Low weight
- Can be optimised for capacity or rate.
- Individual cells up to 1000Ah capacity available.
- Can be discharged at the 40C rate. The high discharge rate means that for automotive use the required cold cranking power or boost power for hybrid vehicles can be provided by a lower capacity battery.
- Fast charge possible.
- Can be deep cycled. The cell maintains a constant voltage for over 80% of its discharge curve. It thus delivers full power down to 80% DOD versus 50% for Lead acid. This means that in practice, for a given capacity, more of the stored energy is usable or that the battery will accept more starting attempts or boost power requests before becoming effectively discharged.
- Very low self discharge rate. Can retain charge for up to ten years.
- Very high coulombic efficiency (Capacity discharged over Capacity charged) of almost 100%. Thus very little power is lost during the charge/discharge cycles.
- No memory effect. No reconditioning needed.
- Tolerates microcycles
- Long cycle life. Cycle life can be extended significantly by using protective circuits to limit the permissible DOD of the battery. This mitigates against the high initial costs of the battery.
- Does not need reconditioning as do nickel based batteries.
- Variants of the basic cell chemistry allow the performance to be tuned for specific applications.
- Available in a wide range of cell constructions with capacities from less than 500 mAh to 1000 Ah from a large number (over 100) of suppliers world-wide.

Shortcomings

Internal impedance higher than equivalent NiCads

For high power applications which require large high cost batteries the price premium of Lithium batteries over the older Lead Acid batteries becomes a significant factor, impeding widespread acceptance of the technology. This in turn has discouraged investment in high volume production facilities keeping prices high and has for some time discouraged take up of the new technology. This is gradually changing and Lithium is also becoming cost competitive for high power applications.

Stability of the chemicals has been a concern in the past. Because Lithium is more chemically reactive special safety precautions are needed to prevent physical or electrical abuse and to maintain the cell within its design operating limits. Lithium polymer cells with their solid electrolyte overcome some of these problems.

Stricter regulations on shipping methods than for other cell chemistries.
Degrades at high temperatures.
Capacity loss or thermal runaway when overcharged.
Degradation when discharged below 2 Volts.
Venting and possible thermal runaway when crushed.
Need for protective circuitry.

Measurement of the state of charge of the cell is more complex than for most common cell chemistries. The state of charge is normally extrapolated from a simple measurement of the cell voltage, but the flat discharge characteristic of lithium cells, so desirable for applications, renders it unsuitable as a measure of the state of charge and other more costly techniques such as coulomb counting have to be employed.

Although Lithium cell technology has been used in low power applications for some time now, there is still not a lot of field data available about long term performance in high power applications. Reliability predictions based on accelerated life testing however shows that the cycle life matches or exceeds that of the most common technologies currently in use.

These drawbacks are far out weighed by the advantages of Lithium cells and are now being used in an ever widening range of applications.

Charging Lithium Batteries

Should be charged regularly.
The cell voltage is typically 4.2 Volts
Battery lasts longer with partial charges rather than full charges.

Charging to 4.1 Volts will increase the cycle life but reduces the effective cell capacity by about 10%.

Can not tolerate overcharging and hence should not be trickle charged.

Charging method: Constant Current - Constant Voltage .

Fast chargers typically operate during the constant current charging phase only when the charging current is at a maximum. They switch off at the point when the constant voltage, reducing current phase starts. At this point the battery will only be charged to about 70% of its capacity.

Applications

Rechargeable Lithium cells are used a wide range of consumer products including cameras, camcorders, electric razors, toothbrushes, calculators, medical equipment, communications equipment, instruments, portable radios and TVs, pagers and PDA's.

They are fast replacing Nickel Metal Hydride cells as the preferred power in mobile phones. Laptop computers almost exclusively use Lithium batteries.

Now high power versions of up to 1000Ah capacity and more are becoming available for use in traction applications in electric and hybrid vehicles as well as for standby power.

Costs

The price of Lithium cells continues to fall as the technology gains more acceptance.

The target price for high power cells is around $300/kWh but cell makers are still quite some way from achieving that.

Although Lithium secondary batteries may cost two or three times more than the cost of equivalent Lead acid batteries and even more when the necessary battery management electronics are thaken into account, this is more than compensated for by their longer cycle life which may be five to ten times the life of Lead acid batteries. Valid cost comparisons should therefore take into account the lifetime costs as well as the initial capital costs.

Lithium Cell Chemistry Variants

Lithium's unique properties have been used as a basis of numerous battery chemistries both for primary and secondary cells. Using nano - electrode materials provides a bigger active surface area and hence a higher current carrying capacity. This technology allows current rates of 10 C or more making the cells suitable for HEV applications.

Lithium-ion

Lithium-ion batteries were designed to overcome the safety problems associated with the highly reactive properties of Lithium metal.

The essential feature of the Lithium ion battery is that at no stage in the charge-discharge cycle should there be any Lithium metal present. Rather, Lithium ions are intercalated into the positive electrode in the discharged state and into the negative electrode in the charged state and move from one to the other across the electrolyte.

Lithium-ion batteries thus operate based on what is sometimes called the "rocking chair" or "swing" effect. This involves the transfer of Lithium ions back and forth between the two electrodes. The anode of a Lithium-ion battery is composed of Lithium, dissolved as ions, into a carbon or in some cases metallic Lithium. The cathode material is made up from Lithium liberating compounds, typically the three electro-active oxide materials, Lithium Cobalt-oxide $LiCoO_2$, Lithium Manganese-oxide $LiMn_2O_4$, and Lithium Nickel-oxide $LiNiO_2$

Lithium salt constitutes the electrolyte.

The origin of the cell voltage is then the difference in free energy between Li^+ ions in the crystal structures of the two electrode materials.

Lithium-ion cells have no memory effect and have long cycle life and excellent discharge performance. For safety reasons, charge control circuitry is required for virtually all Lithium-ion applications.

Lithium-ion technology uses a liquid or gel type electrolyte. This cell chemistry and construction permits very thin separators between the electrodes which can consequently be made with very high surface areas. This in turn enables the cells to handle very high current rates making them ideal for use in high power applications. Some early cells used flammable active ingredients which required substantial secondary packaging to safely contain these potentially hazardous chemicals. This additional packaging not only increased the weight and cost, but it also limited the size flexibility. Modern cell chemistries and additives have essentially eliminated these problems.

Lithium-ion Polymer

Lithium-ion polymer batteries use liquid Lithium-ion electrochemistry in a matrix of ion conductive polymers that eliminate free electrolyte within the cell. The electrolyte thus plasticises the polymer, producing a solid electrolyte that is safe and leak resistant. Lithium polymer cells are often called Solid State cells.

Because there's no liquid, the solid polymer cell does not require the heavy protective cases of conventional batteries. The cells can be formed into flat sheets or prismatic (rectangular) packages or they can be made in odd shapes to fit whatever space is available. As a result, manufacturing is simplified and batteries can be packaged in a foil. This provides added cost and weight benefits and design flexibility. Additionally, the absence of free liquid makes Lithium-ion polymer batteries more stable and less vulnerable to problems caused by overcharge, damage or abuse.

Solid electrolyte cells have long storage lives, but low discharge rates.

There are some limitations on the cell construction imposed by the thicker solid electrolyte separator which limits the effective surface area of the electrodes and hence the current carrying capacity of the cell, but at the same time the added volume of electrolyte provides increased energy storage. This makes them ideal for use in high capacity low power applications.

Despite the above comments there are some manufacturers who make cells designated as Lithium polymer which actually contain a liquid or a gel. Such cells are more prone to swelling than genuine solid polymer cells.

Other Lithium Cathode Chemistry Variants

Numerous variants of the basic Lithium-ion cell chemistry have been developed. Lithium Cobalt and Lithium Manganese were the first to be produced in commercial quantities but Lithium Iron Phoshate is taking over for high power applications because of its improved safety performance. The rest are either at various stages of development or they are awaiting investment decisions to launch volume production.

While the basic technology is well known, there is a lack of operating experience and hence system design data with some of the newer developments which also hampers their adoption. At the same time patents for these different chemistries tend to be held by rival companies undertaking competitive developments with no signs of industry standardisation or adoption of a common product. (The original patent on Lithium Cobalt technology has now expired which is perhaps one explanation for its popularity).

Lithium Cobalt $LiCoO_2$

Lithium Cobalt is a mature, proven, industry-standard battery technology that provides long cycle life and very high energy density. The polymer design makes the cells inherently safer than "canned" construction cells that can leak acidic electrolyte fluid under abusive conditions. The cell voltage is typically 3.7 Volts. Cells using this chemistry are available from a wide range of manufacturers.
The use of Cobalt is unfortunately associated with environmental and toxic hazards.

Lithium Manganese $LiMn_2O_4$

Lithium Manganese provides a higher cell voltage than Cobalt based chemistries at 3.8 to 4 Volts but the energy density is about 20% less. It also provides additional benefits to Lithium-ion chemistry, including lower cost and higher temperature performance. This chemistry is more stable than Lithium Cobalt technology and thus inherently safer but the trade off is lower potential energy densities. Lithium Manganese cells are also widely available but they are not yet as common as Lithium Cobalt cells.

Manganese, unlike Cobalt, is a safe and more environmentally benign cathode material.

Lithium Nickel $LiNiO_2$

Lithium Nickel based cells provide up to 30% higher energy density than Cobalt but the cell voltage is lower at 3.6 Volts. They also have the highest exothermic reaction which could give rise to cooling problems in high power applications. Cells using this chemistry are therefore not generally available.

Lithium (NCM) Nickel Cobal Manganese - $Li(NiCoMn)O_2$

Tri-element cells which combine improved safety with low cost without compromising performance.

Lithium Iron Phosphate $LiFePO_4$

Phosphate based technology possesses superior thermal and chemical stability which provides better safety characteristics than those of Lithium-ion technology made with other cathode materials. Lithium phosphate cells are incombustible in the event of mishandling during charge or discharge, they are more stable under overcharge or short circuit conditions and they can withstand high temperatures without decomposing. When abuse does occur, the phosphate based cathode material will not burn and is not prone to thermal runaway. Phosphate chemistry also offers a longer cycle life.

Recent developments have produced a range of new environmentally friendly cathode active materials based on Lithiated transition metal phosphates for Lithium-ion applications.

Doping with transition metals changes the nature of the active materials and enables the internal impedance of the cell to be reduced.

The operating performance of the cell can also be be "tuned" by changing the identity of the transition metal. This allows the voltage as well as the specific capacity of these active materials to be regulated. Cell voltages in the range 2.1 to 5 Volts are possible.

Phosphates significantly reduce the drawbacks of the Cobalt chemistry, particularly the cost, safety and environmental characteristics. Once more the trade off is a reduction of 14% in energy density, but higher energy variants are being explored.

Due to the superior safety characteristics of phosphates over current Lithium-ion Cobalt cells, batteries may be designed using larger cells and potentially with a reduced reliance upon additional safety devices.

The use of Lithium Iron Phosphate chemistry is the subject of patent disputes and some manufacturers are investigating other chemistry variants mainly to circumvent the patent on the $LiFePO_4$ chemistry.

Lithium Metal Polymer

Developed specifically for automotive applications employing 3M polymer technology and independently in Europe with technology from the Fraunhofer Institute, they have been trialled successfully in PNGV project demonstrators in the USA. They use metallic

Lithium anodes rather than the more common Lithium Carbon based anodes and metal oxide (Cobalt) cathodes.

Some versions need to work at temperatures between 80 and 120ºC for optimum results although it is possible to operate at reduced power at ambient temperature.

The Fraunhofer technology uses an organic electrolyte and the cell voltage is 4 Volts. It is claimed that their the cell chemistry is more tolerant to abuse.

These products are not yet in volume production.

Lithium Sulphur Li_2S_8

Lithium Sulphur is a high energy density chemistry, significantly higher than Lithium-ion metal oxide chemistries. This chemistry is under joint development by several companies but it is not yet commercially available. Lithium Sulphur cells are tolerant of over-voltages. The cell voltage is 2.1 Volts

Alternative Anode Chemistry (LTO)

The anodes of most Lithium based secondary cells are based on some form of carbon (graphite or coke). Recently Lithium Titanate Spinel ($Li_4Ti_5O_{12}$) has been introduced for use as an anode material providing high power thermally stable cells with improved cycle life.

This has the following advantages

- Does not depend on SEI Layer for stability
- No restriction on ion flow hence significantly higher charge and discharge rates possible as well as better low temperature performance.
- Lower internal impedance of the cell
- Higher temperatures can be tolerated.
- No SEI build up over time means very long cycle life possible
- Public domain technology (No patent disputes)

Disadvantages are

- Lower anode reactivity means cell voltage reduced to 2.25 Volts when used with Spinel cathode. (Other cathode chemistries possible)
- Lower energy density hence bulkier cells

Lithium Air Cells

Originally conceived as primary cells (see Lithium Pimary Cells), they offer a very high energy density. Rechargeable versions are now under development. There are potential safety concerns with the metallic Lithium anodes.

See note on the **Toxicity** of Lithium

History

See also Lithium primary cells

Cell Chemistry Comparison Chart

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Lithium Battery Manufacturing

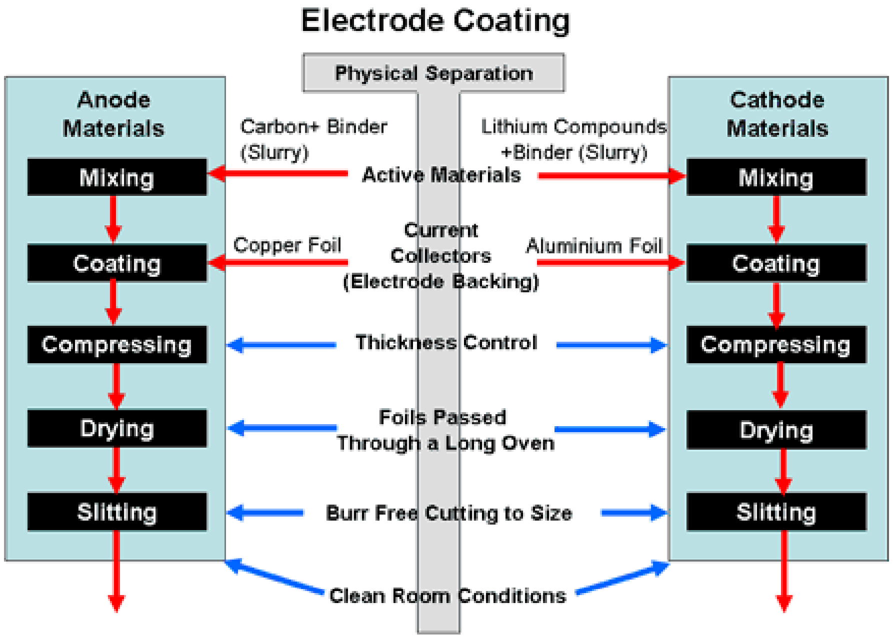
The processes used for manufacturing Lithium batteries are very similar to those used in the production of Nickel Cadmium cells and Nickel Metal Hydride cells with some key differences associated with the higher reactivity of the chemicals used in the Lithium cells.

Electrode Coating

The anodes and cathodes in Lithium cells are of similar form and are made by similar processes on similar or identical equipment. The active electrode materials are coated on both sides of metallic foils which act as the current collectors conducting the current in and out of the cell. The anode material is a form of Carbon and the cathode is a Lithium metal oxide. Both of these materials are delivered to the factory in the form of black powder and to the untrained eye they are almost indistinguishable from eachother. Since contamination between the anode and cathode materials will ruin the battery, great care must be taken to prevent these materials from coming into contact with eachother. For this reason the anodes and cathodes are usually processed in different rooms.

The metal electrode foils are delivered on large reels, typically about 500 mm wide, with copper for the anode and aluminium for the cathode, and these reels are mounted directly on the coating machines where the foil is unreeled as it is fed into the machine through precision rollers.

The coating process is shown in the diagram below



The first stage is to mix the electrode materials with a conductive binder to form a slurry which is spread on the surface of the foil as it passes into the machine. A knife edge is located just above the foil and the thickness of the electrode coating is controlled by adjusting the gap between the knife edge and the foil.

From the coater, the coated foil is fed directly into a long drying oven to bake the electrode material onto the foil. As the coated foil exits the oven it is re-reeled.

The coated foils are subsequently fed into slitting machines to cut the foil into narrower strips suitable for different sizes of electrodes. Later they are cut to length. Any burrs on the edges of the foil strips could give rise to internal short circuits in the cells so the slitting machine must be very precisely manufactured and maintained.

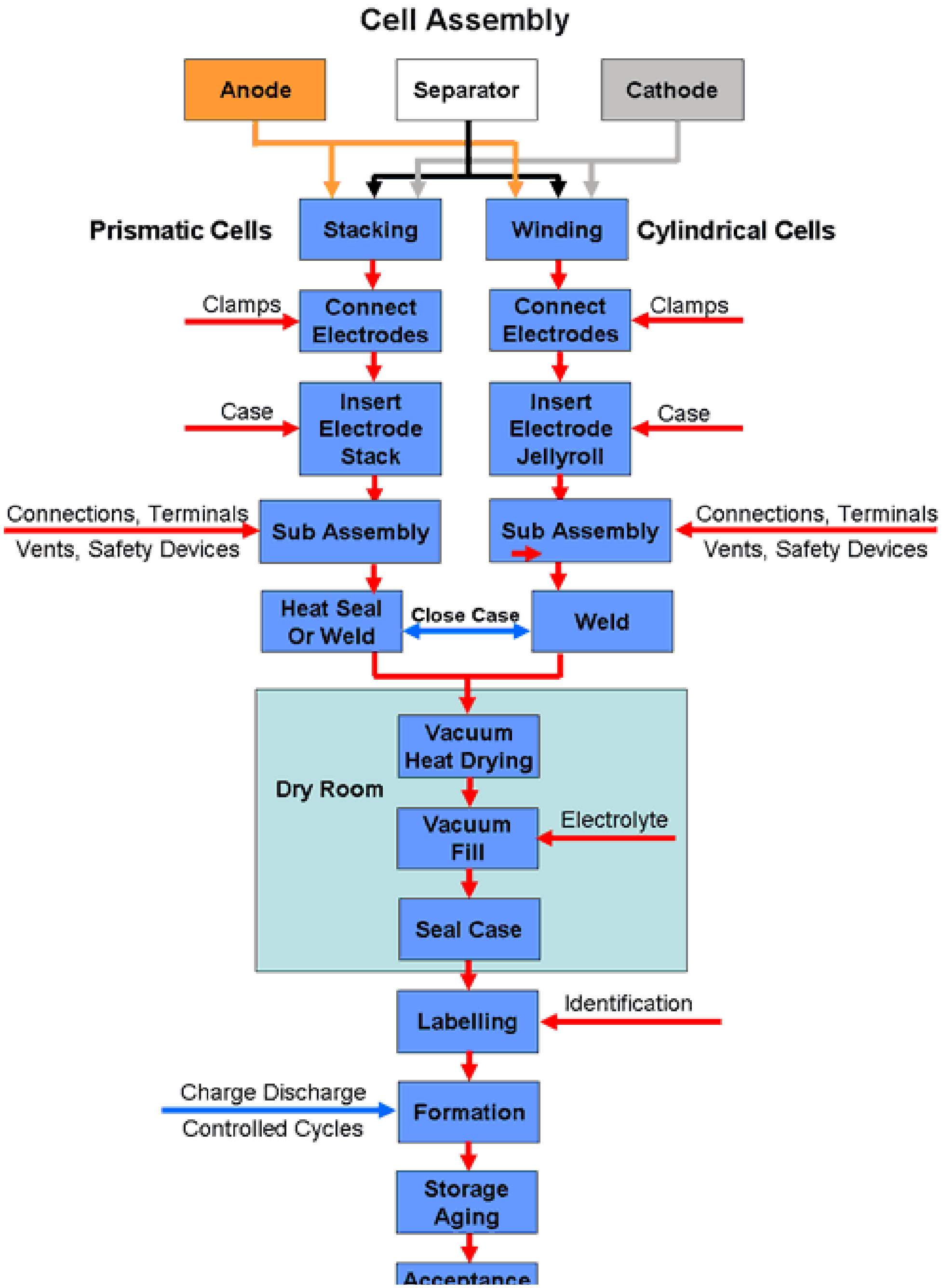
Cell Assembly

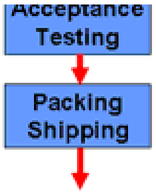
In the best factories cell assembly is usually carried out on highly automated equipment, however there are still many smaller manufacturers who use manual assembly methods.

The first stage in the assembly process is to build the electrode sub-assembly in which the separator is sandwiched between the anode and the cathode. Two basic electrode structures are used depending on the type of cell casing to be used, a stacked structure for use in prismatic cells and a spiral wound structure for use in cylindrical cells.

See Cell Constuction for a description of Stacked and Wound cells.

The assembly process for prismatic and cylindrical cells is illustrated in the following diagram.





- **Prismatic Cells**

  Prismatic cells are often used for high capacity battery applications to optimise the use of space. These designs use a stacked electrode structure in which the anode and cathode foils are cut into individual electrode plates which are stacked alternately and kept apart by the separator. The separator may be cut to the same size as the electrodes but more likely it is applied in a long strip wound in a zig zag fashion between alternate electrodes in the stack.

  While this case design makes optimum use of space when used in a battery pack, it has the disadvantage that it uses multiple electrode plates which need a clamping mechanism to connect all the anodes together and to the main terminal post and a similar mechanism for the cathodes. This all adds to the complexity and labour content of the cell and consequently to the costs.

  Some prismatic cells are also made by the simpler method of winding the electrodes on a flat mandrel. (See below)

  Stacked electrodes are also used for the production of pouch cells.

- **Cylindrical Cells**

  For cylindrical cells the anode and cathode foils are cut into two long strips which are wound on a cylindrical mandrel, together with the separator which keeps them apart, to form a jelly roll (Swiss roll in the UK). Cylindrical cells thus have only two electrode strips which simplifies the construction considerably.

  A single tab connects each electrode to its corresponding terminal, although high power cells may have multiple tabs welded along the edges of the electrode strip to carry the higher currents.

The next stage is to connect the electrode structure to the terminals together with any safety devices and to insert this sub-assembly into the can. The can is then sealed in a laser welding or heating process, depending on the case material, leaving an opening for injecting the electrolyte into the can.

The following stage is to fill the cell with the electrolyte and seal it. This must be carried out in a "dry room" since the electrolyte reacts with water. Moisture will cause the electrolyte to decompose with the emission of toxic gases. Lithium Hexafluoride (LiPF6) for instance, one of the most commonly used electrolyte materials, reacts with water forming toxic hydrofluoric acid (HF).

Afterwards the cell is given an identification with a label or by printing a batch or serial number on the case.

Formation

Once the cell assembly is complete the cell must be put through at least one precisely controlled charge / discharge cycle to activate the working materials, transforming them into their useable form. Instead of the normal constant current - constant voltage charging curve, the charging process begins with a low voltage which builds up gradually. This is called the Formation Process. For most Lithium chemistries this involves creating the SEI (solid electrolyte interface) on the anode. This is a passivating layer which is essential for moderating the charging process under normal use.

During formation, data on the cell performance is gathered and recorded for quality analysis and traceability.

Process Control

Tight tolerances and strict process controls are essential throughout the manufacturing process. Contamination, physical damage and burrs on the electrodes are particularly dangerous since they can cause penetration of the separator giving rise to internal short circuits in the cell and there are no protection methods which can prevent or control this.

Support Services

Cleanliness is essential to prevent contamination and cells are normally manufactured in clean room conditions with controlled access to the assembly facilities often via air showers.

Apart from the production test equipment, a battery manufacturer should be expected to have a materials laboratory equipped to carry out a full analysis of the materials used in the production of the cells as well as to carry out failure analysis. The following list shows some of the major equipment used.

- Scanning electron microscope (SEM) for investigating the physical structure of the materials
- Mass spectrometer for analysing the chemical content of the materials
- Calorimeters for checking the thermal properties of the materials and the cells
- Programmable charge/discharge cycle test equipment to exercise the cells and verify their lifetime
- Environmental chambers and vibration tables for investigating the performance of the cells under their expected operating conditions
- Mechanical stress tesing equipment

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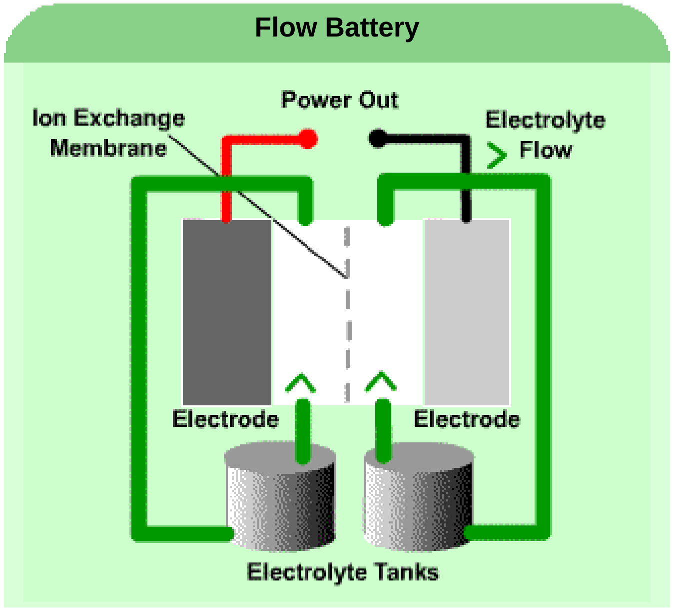
Flow Batteries

Flow batteries allow storage of the active materials external to the battery and these reactants are circulated through the cell stack as required. The first such battery was Zinc/chlorine battery in which the chlorine was stored in a separate cylinder. It was first used in 1884 by Charles Renard to power his airship La France which contained its own on board chlorine generator.

The technology was revived in the mid 1970s.



Flow Battery

Modern flow batteries are generally two electrolyte systems in which the two electrolytes are pumped through the cell. The great advantage that this system provides is the almost unlimited electrical storage capacity, the limitation being only the capacity of the electrolyte storage reservoirs. Opportunities for thermal management are also facilitated by using the electrolyte as the thermal working fluid as it is pumped through the cells. High power batteries are constructed using a multiple stack of cells in a bipolar arrangement.

The Zinc-Bromine battery is a modern example of a flow battery. It is based on the reaction between two commonly available chemicals, Zinc and Bromine. The battery consists of a Zinc negative electrode and a Bromine positive electrode separated by a microporous separator. An aqueous solution of Zinc Bromide is circulated through the two compartments of the cell from two separate reservoirs. The other electrolyte stream in contact with the positive electrode contains Bromine. The Bromine storage medium is immiscible with the aqueous solution containing Zinc Bromide.

The battery uses electrodes that cannot and do not take part in the reactions but merely serve as substrates for the reactions. There is therefore no loss of performance, as in most rechargeable batteries, from repeated cycling causing electrode material deterioration. When the Zinc-Bromine battery is completely discharged, all the metal Zinc plated on the negative electrodes is dissolved in the electrolyte and again produced the next time the battery is charged. In the fully discharged state the Zinc-Bromine battery can be left indefinitely.

Energy densities three times better than Lead Acid batteries are claimed.

The flow battery technologies provide very high power and very high capacity batteries for load levelling applications on the national electricity grid system.

The so called Redox Battery is an example of a two electrode flow system.

The Regenesys Sodium Polysulfide Bromine battery is another example.

These are very high cost systems and so far there are very few successful installations.

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Zinc Air Batteries

Characteristics

An example of Metal Air batteries, cells using zinc-air technology are energized only when atmospheric oxygen is absorbed into the electrolyte through a gas-permeable, liquid-tight membrane. With the removal of a sealing tab, oxygen from the air is introduced into the cell. A zinc-air battery usually reaches full operating voltage within 5 seconds of being unsealed.

The zinc air cell is basically a primary battery however rechargeable designs for high power applications are possible by physically replacing the zinc electrodes.

They use the oxygen content of the air as active mass. The positive electrode is a porous body made of carbon with air access. Atmospheric oxygen is reduced at this electrode. The active mass is thus not contained in the electrode but is taken from the surrounding air as it is needed. The initial weight of the battery is reduced accordingly. The negative electrode consists of zinc. An aqueous solution of potassium hydroxide serves as the electrolyte.

The cell voltage for the chemistry is theoretically capable 1.65 Volts however almost all designs are optimised for less than 1.4 or 1.3 Volts in order to achieve longer lifetimes.

Advantages

High energy density but low power

Inexpensive materials

The zinc-air system, when sealed, has excellent shelf life, with a self-discharge rate of only 2 percent per year.

In relation to their physical size, Zinc/Air batteries store more energy per unit of weight (in terms of 220 Wh/kg) than almost any other primary type.

Primary cells available in a range of button and coin cell sizes.

Rechargeable high power cells available for traction applications.

Shortcomings

Sensitive to extreme temperature and humid conditions.

Carbon dioxide from the air forms carbonate which reduces conductivity.

High self discharge.

After activation, chemicals tend to dry out and the batteries have to be used quickly.

Although recharging is possible it is also inconvenient and is only suitable for high power types.

High internal resistance which means zinc air batteries must be huge to satisfy high current needs.

High power batteries such as those designed for traction applications use mechanical charging in which discharged zinc cartridges are replaced by fresh zinc cartridges. The used cartridges are subsequently recycled.

Applications

The system is well known as a primary battery.

Zinc air button cells are commonly used for watches and hearing aids.

Larger types are employed as prismatic or cylindrical cells for telecoms and railway remote signalling, safety lamps at road and rail construction sites or as power sources for electric fences.

Possible traction applications where "Mechanical Charging" cuts down on recharging time but little take up so far.

Costs

Low cost

History

See also Metal Air Cells

Cell Chemistry Comparison Chart

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Charger Specification Checklist

The need to specify a matching charger for the chosen battery technology can not be over emphasised. As pointed out in the section about Chargers the use of an inappropriate charging method can seriously shorten the life of a battery or even kill it outright. A well designed "Intelligent Charging System" however can extend the life of the battery.

As with batteries, most of the information needed to specify a charger for a particular application is listed on the "Charger Quotation" page and in the main this should be self explanatory. Some further explanation is however given below.

In specifying chargers there are some factors which are mandatory and some which are optional.

Essentials

- The most important requirement of a charger is that it should be appropriate for the cell chemistry of the chosen battery since the use of unsuitable chargers can damage the battery. The section on Chargers describes some of the many options available.
- There should be some method of protecting against overcharging. The specification should indicate whether this is to be incorporated in either the battery or the charger.
- The charger design should also match the intended use profile of the battery. Will it be off line charging only? Is trickle charging required? Is float charging required?
- The desired charging time must be specified.
- The capacity of the charger should be sufficient to charge the battery within the desired time.
- The power source must be specified. This could be the AC mains, DC battery power, opportunity (variable) charging from vehicle, solar or wind sources or a combination of these.
- For high power applications the charger performance (efficiency, inrush current handling, power factor) becomes significant.

Options

See also Charger Types

- There will be trade offs to be made in the design of the actual charger usually between efficiency and cost. Different types of voltage regulators such as "switch mode" , "linear" or "buck" may be used.
- The charger may be integrated with the battery electronics to form an Intelligent Charging System. Although complex, such a system can significantly prolong the battery life.

- The charger may also incorporate a data logging facility, to identify individual batteries and store key data about their history.
- There is always the possibility to add lights to indicate the progress of the charge and or warning lights.

Ask for a quotation

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Charger Quotation Request

(Supplementary Information)

Please note that Woodbank Communications does not sell chargers. We will however pass on your request to a potential supplier. These facilities are only available to bona fide business partners and are only intended for high volume purchases of custom chargers, not for standard off-the-shelf products or low volume specials.

Please check the FAQ number 2 before you fill in the form.

This form should be completed in conjunction with the information given on the battery quotation form.

Go to "**How to Specify Chargers**" if you need help with the questions.

Battery Application	Application				
Batteries Specified (If known)	No preference				
Quantity Required					
Prototypes		Units			
Annual Requirement		Units			
Battery Voltage		Volts			
Battery Storage Capacity		mAh			
Battery Current Capacity		mA			
Inrush Current (If known)		mA			
Charging Time		Minutes			
Charger Power Supply					
AC		Volts		Hertz	Phases
DC		Volts			
Other inputs		Please specify			
Battery temperature detection required	○ Yes ○ No ● Don't know				
EMC restrictions	Tick any which apply				

Emissions ☐
Susceptibility ☐
Don't know ☐

Safety Approvals Required Tick any which apply

UL ☐
CE ☐
FCC ☐
TUV ☐
CSA ☐
NF ☐

ISO9000 ☐
QS9000 ☐
DEF ☐
MIL ☐
Other ☐
Don't know ☐

Any questions or special requirements ?

Please tell us your email address so that we can relate this information to your battery quotation.

Name
Company
Telephone
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Shipping Lithium Batteries

International Regulations for the Transportation of Lithium Ion Battery Packs

New regulations governing the shipment of lithium batteries are coming into force. They involve testing the cells to ensure safety during transpiration.

Background

In Dec'00 the United Nations (UN) passed a recommendation relating to the safe transport of all Lithium Ion (Li-Ion) cells and batteries. Subject to product testing, the legislation allows for some ' *smaller* ' Li-Ion batteries to be transported as normal cargo. However some ' *larger* ' Li-Ion batteries are to be regarded as **Class 9 - Hazardous Goods.**

Legislation

In January 2003 new regulations affecting packaging, labeling& testing of cells & new packs came into effect. From January 2005 the regulations will apply to all packs including any pre-2003 designs.

Interaction and Implementation

The UN makes recommendations which are adopted by global regulatory bodies including International Air Transport Association (IATA) and the International Civil Aviation Organisation (ICAO) and individual countries pass enabling legislation. The effect of the new rules is that the various transport agencies are in progressively implementing the UN recommendation. Individual governments (including the EC) are believed to be progressively passing adoptive legislation.

Responsibilities

- Shippers - have to ensure that all the documents required for product shipment are in place.
- Cell Manufacturers - need to test ' *qualifying* ' cells, otherwise goods will be classified Class 9
- Pack Assemblers - must test all new designs immediately
- Pre 2003 designs need to be tested before 2005 otherwise goods will be classified as Class 9

To Qualify as Small Batteries

The exception to Class 9 is that cells & batteries below a specific equivalent weight of Lithium can be shipped as normal cargo. The maximum '*equivalent weight* ' allowed is defined as 1.5 grams per cell and / or 8.0 grams per battery pack.

The ' *equivalent weight* ' is calculated as follows:-

Equivalent Lithium = Cell Capacity (Ah) x 0.3 grams

For example 1.8Ah x 0.3 x 2 cells = 1.08 grams

Legislation

- Normal Cargo - Under the new legislation once tested, shipments can be shipped as normal cargo providing they are packaged, labeled and documented to the new procedure
- Class 9 Cargo - under the new legislation all cells and battery packs above this limit must still pass the required test and be shipped as Class 9.

Exempt products

- Nickel Cadmium (NiCd) - not affected
- Nickel Metal Hydride (NiMH) - not affected
- Lithium Ion (Li-Ion) - exclusions
  - Batteries carried for personal use
  - Batteries installed within equipment

Self Certification

Self Certification by suppliers is permitted and most cell suppliers have, or are in the process of completing the required testing. Battery pack assemblers have also initiated testing of new products

Battery Tests

In order to ship as normal cargo the cells and batteries must pass a series of tests. If engineering models and prototypes need to be shipped prior to completion of the tests then they must be shipped as Hazardous Class 9 Materials.

- Test 1 - Altitude Simulation - simulates air transport under low pressure conditions.
- Test 2 - Thermal - assesses the integrity of the cell's seal and the internal electrical connections of the battery.
- Test 3 - Vibration - simulates vibration during transport.
- Test 4 - Shock - simulates possible impacts during transport.
- Test 5 - External Short Circuit - simulates an external short circuit condition.
- Test 6 - Impact - simulates an in-transit impact.

- Test 7 - Overcharge - simulates an in-transit impact.
- Test 8 - Forced Discharge - evaluates the ability of a rechargeable battery to withstand a forced discharge condition.

NOTE- The above tests need to be carried out on both the bare cells and assembled battery packs except tests 6 & 8 which only apply to the cells and test 7 which only applies to the assembled battery pack.

See also UN Shipping Regulations for Lithium Batteries

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Battery Communications Interfaces

Many battery applications require communications with other system devices or with external equipment. These are often called Intelligent Batteries. This may simply be a data link used for performance monitoring, for data logging, for diagnostics, or for setting system parameters or it may be a communications channel carrying system control signals. The choice of the communications protocol is determined not by the battery but by the application in which it is to be used.

Data buses

RS232 connection - A standard for serial transmission of data between two external devices with cable lengths up to 50 feet. Separate transmit and receive lines provide full duplex communication. Used for data rates up to 20,000 bits per second.

EIA-485 (formerly RS485) connection - A standard for serial transmission of data between multiple devices with cable lengths up to 4000 feet. (Possible 32 channels). Normally half duplex, it uses a differential balanced line over twisted pair for noise immunity and does not specify or recommend any particular data protocol. Suitable for data rates up to 100K bits per second or 10M bits per second depending on the length of the cables.

Inter - Integrated Circuit (I^{2}C) Bus

The (I^{2}C) Bus was originally designed for use between internal modules within a system rather than for external communications. It is a bidirectional, half duplex, two wire synchronous bus. It runs with data rates up to 3.4 Mbits/s and is suitable for Master - Slave applications. Multiple slaves are possible but only a master can initiate a data transfer.

Typically used for internal communications within embedded systems such as a BMS.

CAN Bus

The industry standard for on-board vehicle communications is the CAN (Controller Area Network) bus. It was originally designed in the 1980s by Bosch in Germany with the purpose of eliminating hundreds of wires from the wiring harness, reducing the size and weight of the wiring loom by multiplexing the signals on to a single shared broadcast data bus. The CAN bus is defined as a two wire, serial communications bus designed for networking intelligent sensors and actuators in a centralised multiplexing system. It is now accepted as an ISO standard.

The CAN Bus allows 12 Volts, or other potential, power to be distributed around the vehicle (or system) on a single power rail with local actuators connecting the power to each application as needed. Vehicle functions such as temperatures , alarms or the positions of switches are monitored by sensors connected to the bus and the controller can direct the actuators to initiate the appropriate response as required.

Two variants are available to suit different transmission rates. A high speed (1 MBaud) bus is used for rapid control devices for operations such as engine management and vehicle stability and motion control. For simple switching and control of functions such as lighting, windows, mirror adjustment and instrument displays a low speed (100 KBaud) bus is used.

The CAN bus was designed to provide secure communications in the very harsh operating environments with high levels of electrical noise which are found in automotive systems.

The communications protocol defines the following:

- Method of addressing the devices connected to the bus
- Data word format (The message)
- Priority setting
- Transmission sequence
- Control signals
- Error detection
- Error handling or correction
- Transmission speed

The message data, the control signals and the error correction are contained in a data frames of equal length which are transmitted sequentially over the transmission channel.

Because each device connected to the bus contains its own intelligence, each station in effect monitors its own output, interrupts disturbed transmissions and acknowledges correct transmissions. Thus faults can be detected and the appropriate actions taken.

Standard CAN microcontrollers are available from a variety of semiconductor manufacturers.

Automotive BMS therefore uses the CAN bus as its main communications channel.

LIN Bus

The LIN Bus is another automotive communications standard, initiated in 1998, similar to the CAN Bus.

It is a single wire Local Interconnect Network operating at 20 KBaud using distributed multipexers and standardised Smart Connectors based on standard UART/SCI IC hardware allowing for simple, low cost IC solutions. It uses more electronics than the CAN Bus but it is more flexible and uses less wiring.

Although the LIN Bus was conceived for automotive applications, its implementation is not confined to such uses. It can for instance be used to control complex household appliances such as dishwashers and washing machines.

FlexRay Bus

The new FlexRay Bus has been developed recently in response to the demands of more complex control applications such as drive by wire, steer by wire, brake by wire and ever more sophisticated engine management systems planned for future automotive use. It provides a fault tolerant 10Mbit/sec data rate on each of two channels enabling both synchronous and asynchronous data transfer. The FlexRay data payload per frame is 20 times greater than the CAN Bus.

Unlike event-triggered systems such as the CAN system, FlexRay is based on a time-triggered architecture known as Time Division Multiple Access (TDMA) where communication is organized into repetitive, predefined time slots. TDMA thus allows high priority signals to be guaranteed synchronous access to a channel in predetermined, cyclic time slots, while low priority signals, which are not needed continuously, are transmitted asynchronously and only gain access to the bus as required when the bus is free.

The FlexRay Bus can therefore support fast responding dynamic control systems rather than just the simpler sensors and actuators permitted with the CAN Bus.

SMBus

The SMBus (System Management Bus) is a two wire, 100 KHz, serial bus designed for use with low power Smart Battery Systems (SBS) with the limited objectives of interconnecting Smart Batteries which have built in intelligence, with their associated chargers. Sometimes found in simple vehicle applications, it does not have the range of capabilities for controlling devices connected to the power lines which the CAN and LIN buses have. See Intelligent Batteries for details of Smart Battery Systems.

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Instructions for Use

User safety precautions

Disassembly

Never disassemble a battery, as the materials inside may be toxic and may damage skin and clothes.

Short-circuiting

Never attempt to short-circuit a battery. Doing so can damage the product and generate heat that can cause burns.

Throwing batteries into a fire or water

Disposing of a battery in fire can cause the battery to rupture. Also avoid placing batteries in water, as this may cause the battery to fail.

Soldering

Never solder anything directly to a battery. This can destroy the safety features of the battery by damaging the safety vent inside the cap.

Permanent connections to an energy cell may be made by spot welding solder tags to the terminals. A soldered connection can subsequently be made to the tag.

Inserting the batteries with their polarities reversed

Never insert a battery with the positive and negative poles reversed as this can cause permanent damage to the battery which may swell or rupture.

Charging

Never charge with an unspecified charger or specified charger that has been modified. This can cause breakdown of the battery or swelling and rupturing.

Never attempt to charge a battery which has been physically damaged.

Overcharging at high currents and reverse charging

Never reverse charge or overcharge with high currents (i.e. higher than rated). Doing so causes rapid gas generation and increased gas pressure, thus causing batteries to swell or rupture.

Don't leave the battery in the charger once it is fully charged.

Installation in equipment (with an airtight battery compartment)

Always avoid designing airtight battery compartments. In some cases, gases (oxygen, hydrogen) may be given off, and there is a danger of the batteries bursting or rupturing in the presence of a source of ignition (sparks generated by a motor switch, etc.).

Use of batteries for other purposes

Do not use a battery in an appliance or purpose for which it was not intended. Differences in specifications can damage the battery or appliance.

Short-circuiting of battery packs

Special caution is required to prevent short circuiting any battery since the consequences can be very dangerous. Care must be taken during the design of the battery pack shape to ensure batteries cannot be inserted in reverse. Also, caution must be given to prevent accidental short-circuiting of the battery.

Using old and new batteries together

Avoid using old and new batteries together. Also avoid mixing batteries using differing cell chemistries such as ordinary dry-cell batteries, Ni-Cd, NiMH batteries or with another manufacturer's batteries. Differences in various characteristic values, etc., can cause damage to the batteries or the product.

Storage

Store the batteries in a cool place and when in use don't allow them to remain in environments which may be subject to overheating. (e.g. direct sunlight in a locked car)

ESD (Electrostatic Discharge) Bags

Do not put batteries into plastic bags designed to protect components from electrostatic discharge. These bags are made from conductive material which could cause the battery to be short circuited.

Other Precautions

Batteries should always be charged prior to use. Be sure to charge correctly.

Warning Notice

Be sure to indicate this safety warning clearly in all operating instructions as a handling restriction for ensuring safety

More about Battery Safety .

Still unsure?

Please consult MPower if you need any advice regarding the product design, operating conditIons, and charge and discharge characteristics of your MPower battery.

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State of Health (SOH) Determination

What is the SOH?

The State of Health is a "measurement" that reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery. It takes into account such factors as charge acceptance, internal resistance, voltage and self-discharge.

During the lifetime of a battery, its performance or "health" tends to deteriorate gradually due to irreversible physical and chemical changes which take place with usage and with age until eventually the battery is no longer usable or dead.

The SOH is an indication of the point which has been reached in the life cycle of the battery and a measure of its condition relative to a fresh battery.

Unlike the SOC which can be determined by measuring the actual charge in the battery there is no absolute definition of the SOH. It is a subjective measure in that different people derive it from a variety of different measurable battery performance parameters which they interpret according to their own set of rules. It is an estimation rather than a measurement. This is fine so long as the estimate is based on a consistent set of rules but it makes comparisons between estimates made with different test equipment and methods unreliable.

Battery manufacturers do not specify the SOH because they only supply new batteries. The SOH only applies to batteries after they have started their ageing process either on the shelf or once they have entered service. The SOH definitions are therefore specified by test equipment manufacturers or by the user.

What is the SOH used for?

Its purpose is to provide an indication of the performance which can be expected from the battery in its current condition or to provide an indication of the how much of the useful lifetime of the battery has been consumed and how much remains before it must be replaced. In critical applications such as standby and emergency power plant the SOC gives an indication of whether a battery will be able to support the load when called upon to do so. Knowledge of the SOH will also help the plant engineer to anticipate problems to make fault diagnosis or to plan replacement. This is essentially a monitoring function tracking the long term changes in the battery.

- **SOH for EV applications**

  For EV applications, the ability to achieve the range when called upon to do so is most important, hence the SOH is based on a comparison of current capacity with capacity when new.

- **SOH for HEV applications**

  For HEV applications the ability to deliver the specified power is mos important and so SOH is based on a comparison of the DC resistance (or 1 kHz impedance) now with DC resistance (or 1 kHz impedance) when new.

If the recorded usage history of the battery is used to determine the SOH, as in the Log Book Function below, then this same data can be also used to validate warranty claims. This is particularly useful for assessing the condition of high cost EV and HEV batteries which may have been subject to abuse.

How is the SOH determined?

Any parameter which changes significantly with age, such as cell impedance or conductance, can be used as a basis for providing an indication of the SOH of the cell. Changes to these parameters will normally signify that other changes have occurred which may be of more importance to the user. These could be changes to the external battery performance such as the loss of rated capacity or increased temperature rise during operation or internal changes such as corrosion.

Because the SOH indication is relative to the condition of a new battery, the measurement system must hold a record of the initial conditions or at least a set of standard conditions. Thus if cell impedance is the parameter being monitored, the system must keep in memory as a reference, a record of the initial impedance of a fresh cell. If counting the charge / discharge cycles of the battery is used as a measure of the battery usage, the expected battery cycle life of a new cell would be used as the reference. In a Lithium ion battery, since the cell capacity deteriorates fairly linearly with age or cycle life, the expired, or remaining cycle life, depending on the definition used , is often used as a crude measure of the SOH.

In practice some people estimate the SOH from a single measurement of either the cell impedance or the cell conductance. (See Impedance and Conductance Testing). In pursuit of accuracy, others advocate measuring several cell parameters, all of which vary with the age of the battery, and making an estimation of the SOH from a combination of these factors. Examples are capacity, internal resistance, self-discharge, charge acceptance, discharge capabilities the mobility of electrolyte and cycle counting if possible. The absolute readings will depend on the cell chemistry involved. Weighting is added to individual factors based on experience, the cell chemistry and the importance the particular parameter in the application for which the battery is used. If any of these variables provide marginal readings, the end result will be affected. A battery may have a good capacity but the internal resistance is high. In this case, the SOH estimation will be lowered accordingly. Similar demerit points are added if the battery has high self-discharge or exhibits other chemical deficiencies. The points scored for the cell are compared with the points assigned to a new cell to give a percentage result or figure of merit.

Such complex measurements and processing need the help of a microprocessor to deliver the results. For automated measurements the initial conditions and the "experience" can be encapsulated in memory to facilitate this process. The "experience" can be modified in a learning process as more data becomes available to refine the estimations. Fuzzy Logic is used to combine the experience with the measurements to improve the accuracy of the results.

The sentence on the cell - Pass or Fail -. is based on an arbitrary limit based on experience with the application, expedience and whatever safety factors are required.

This method uses an external measuring device to provide an estimate of the current / actual SOH. It does not require any modifications to the cells.
Proprietary equipment is available for measuring the SOH.

The Log Book Function

An alternative method of specifying the SOH is to base the estimation on the usage history of the battery rather than on some measured parameter. The number of charge - discharge cycles completed by the battery is an obvious measure, but this does not necessarily take into account any extreme operating conditions experienced by the battery which may have affected its functionality. It is however possible to record the duration of any periods during which the battery has been subject to abuse from out of tolerance voltages, currents or temperatures as well as the magnitude of the deviations. From this data a figure of merit representing the SOH can be determined by using a weighted average of the measured parameters.
Battery usage (or abusage) data can be stored in memory in the BMS in a "History Chip" and downloaded when required. This alternative method does not use any external test equipment but it adds complexity and cost to the battery.

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Authentication and Identification

For critical battery applications, or with expensive batteries, authentication is often employed to prevent the use of unapproved batteries in the application. This may be to avoid compatibility problems with system protection and power management schemes or with the applicable software revision or it could be to avoid damage to the reputation of the product and the brand if inferior or unreliable cells would be used.

It could also be used to control the aftermarket in replacement batteries by preventing so called "knock-off" or counterfeit batteries from working in the application.

BMS (Battery Management System)

Authentication by the BMS works by incorporating into the battery pack a unique method of identifying the battery such as a code written into a memory device. The application interrogates the battery, looking for the correct code. If for any reason the code is not found or if it is incorrect, then a switch inside the application will not allow the power to be connected to the rest of the circuit. Only authorised batteries will switch on the power.

Authentication can also be used to restrict the users of the battery application to qualified persons only or it could be arranged to set limits to the maximum current which can be drawn from the battery depending on the level of authority of the user or the location in which the battery is used.

RFID (Radio Frequency Identification)

It is also possible to construct similar identification and authentication schemes using RFID methods.

Holograms

Holograms provide a cheaper alternative method for identifying batteries but they are less suitable for automation. They are easy to read but very difficult to copy, even by computer scanning. They provide a reasonably secure way for the user to verify that the product is genuine. While they can alert the user to counterfeit products they can not normally prevent counterfeiting. Holograms can be used in label form to record production data and to provide traceability in case of quality problems. The label itself can be used for tamper proofing and it can also carry advertising information.

Bar Code Labels

Using bar code labels is the simplest and cheapest method of providing information such as battery type, date of manufacture and serial number with the battery. They are useful for identification, traceability and inventory management but they are not easily read by the user and are not suitable for providing automatic authentication within the product.

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Electric Drives - Motor Controllers and Control Systems
(Description and Applications)

Purpose

For many years the motor controller was a box which provided the motor speed control and enabled the motor to adapt to variations in the load.

Designs were often lossy or they provided only crude increments in the parameters controlled.

Modern controllers may incorporate both power electronics and microprocessors enabling the control box to take on many more tasks and to carry them out with greater precision. These tasks include:

- Controlling the dynamics of the machine and its response to applied loads.

  (speed, torque and efficiency of the machine or the position of its moving elements.)
- Providing electronic commutation.
- Enabling self starting of the motor.
- Protecting the motor and the controller itself from damage or abuse.
- Matching the power from an available source to suit the motor requirements (voltage , frequency, number of phases). This is an example of "Power Conditioning" whose purpose is to provide pure DC or sinewave power free from harmonics or interference. Although it could be an integral part of a generator control system, more generally, power conditioning could also be provided by a separate free standing module operating on any power source.

Control System Principles

- **Open Loop Systems (Manual Control)**

  In an open loop control system the controlling parameters are fixed or set by an operator and the system finds its own equilibrium state.

  In the case of a motor the desired operating equilibrium may be the motor speed or its angular position. The controlling parameters such as the supply voltage or the load on the motor may or may not be under the control of the operator.

  If any of the parameters such as the load or the supply voltage are changed then the motor will find a new equilibrium state, in this case it will settle at a different speed. The actual equilibrium state can be changed by forcing a change in the parameters over which the operator has control.

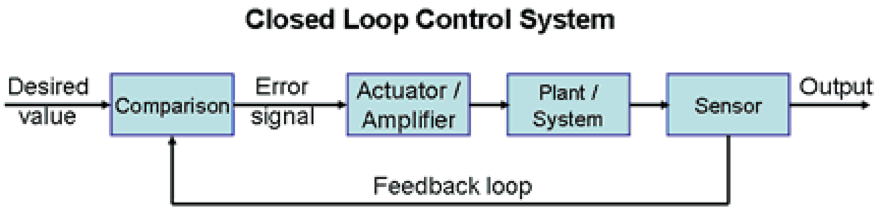
- **Closed Loop Systems (Automatic Control)**

  Once the initial operating parameters have been set, an open loop system is not responsive to subsequent changes or disturbances in the system operating environment such as temperature and pressure, or to varying demands on the system such as power delivery or load conditions.

For continual monitoring and control over the operating state of a system without operator intervention, for more precision or faster response, automatic control systems are needed.

Negative Feedback

To meet these requirements "closed loop" systems are necessary. Also called feedback control systems, or negative feedback systems, they allow the user to set a desired operating state as a target or reference and the control system will automatically move the system to the desired operating point and maintain it at that point thereafter.



A sensor is used to monitor the actual operating state of the system and to feed back to the input of the controller an analogue or digital signal representing the output state. The actual and desired or reference states are continually compared and if the actual state is different from the reference state an error signal is generated which the controller uses to force a change in the controllable parameters to eliminate the error by driving the system back towards the desired operating point.

Loop Gain The error signal is usually very small so the controlling circuit or mechanism must contain a high gain "error amplifier" to provide the controlling signal with the power to affect the change.

The amplification provided in the loop is called the loop gain.

Loop Delay The response is not always instantaneous as there is usually a delay between sensing the error, or aiming at a new position, and eliminating the error or moving to the new desired position. This delay is called the loop delay.

In mechanical systems the delay may be due to the inertia associated with the lower acceleration possible in getting a large mass to move when a force is applied.

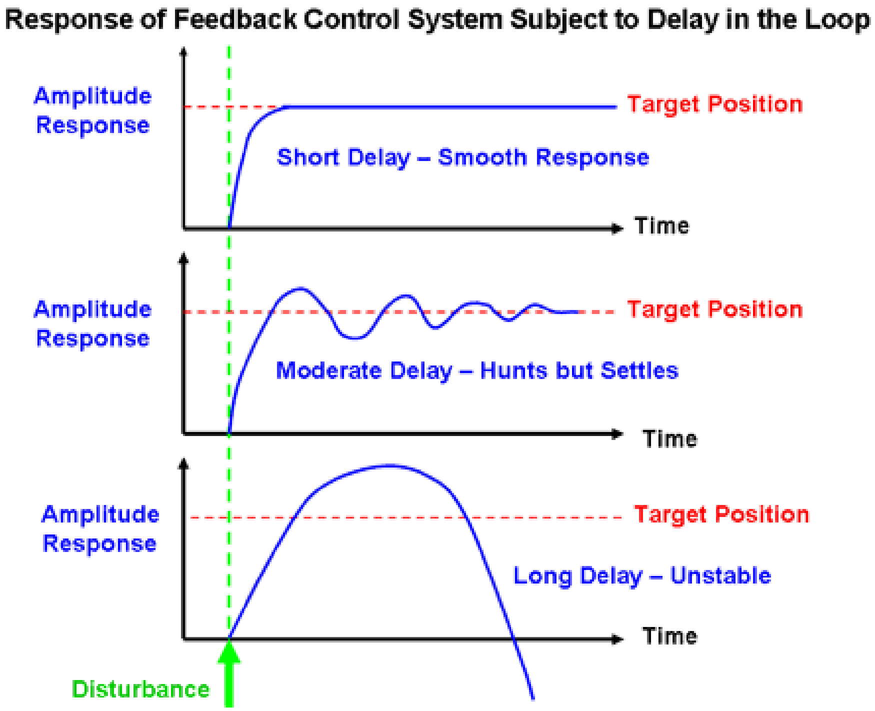
In electrical circuits the delay may be associated with the inductive elements in the circuit which reduce the possible rate of current build up in the circuit when a voltage is applied.

Closed loop control systems must act very quickly to implement the error correction without delay, before the system has time to change to a different state. Otherwise the system will possibly become unstable.

When there is a time lag between sensing of the error and the completion of the corrective action and the loop gain is large enough the system the system may overshoot. If this happens the error will then be in the opposite direction and the control system will also reverse its direction of action in order to correct this new error. The result will be that the actual position will oscillate about the desired position. This instability is called hunting as the system hunts to find its aiming point.

In the worst case, the delayed error correcting response will arrive 180 degrees out of phase with the disturbance it is trying to eleiminate. When this happens the direction of the system response will not act so as to eliminate the error, instead it will reinforce the error. Thus the delay has changed the system response from negative feedback to positive feedback and the system will be critically unstable.

The diagrams below show the response of a control system to a small disturbance.



The Nyquist Stability Criterion is used to predict whether or not a system is unstable from a knowledge of the loop gain and the loop delay as follows

- If the loop gain is unity ot greater at the frequency of an input sinusoid where the time delay in the system is equal to half of a cycle period, the sytem will be unstable.

In practical terms, a system with high electrical or mechanical inertia will have a slow response (long delay). With a low magnitude, error correcting action (mechanical force or electrical voltage) the system will be slow in responding (speeding up) but because it is slow, it will also have a low momentum and will tend to settle at the desired operating point when the error correcting force is removed.

The delay in implementing the corrective action however depends on the loop gain.

If, in the same system, the error correcting force is high (amplified / higher loop gain), as in a fast acting system, the system will respond (get moving) more quickly (shorter delay) but it will have correspondingly higher momentum (higher speed of response). When the error correcting force is removed, like any high inertia system, the system's momentum will keep it moving and it will overshoot the target position. Applying the error signal in the opposite direction to bring the system back to its target will cause it to overshoot in the opposite direction.

Nyquist shows how much delay can be tolerated in a system with unity loop gain and defines the point at which the system becomes unstable

History

In the example of a DC electric motor, the desired operating state may be a particular speed. A tachometer is used to measure the actual speed and this is compared to the reference speed. If it is different, an error signal, whose magnitude and polarity correspond to the difference between the reference and the actual speeds, is fed to a voltage controller to change the motor speed so as to reduce the error signal. When the motor is operating at the desired speed the error signal will be zero and the motor will maintain that speed.

- Three different types of error processing are commonly used in control systems, **P**, **I** and **D**, named after three basic ways of manipulating the error information.
  - **Proportional** - Proportional error correction multiplies the error by a (negative) constant **P**, and adds it to the controlled quantity.
  - **Integral** - Integral error correction incorporates past experience. It integrates the error over a period of time, and then multiplies it by a (negative) constant **I** and adds it to the controlled quantity. Equilibrium is based on the average error and avoids oscillation and overshoot providing a more stable system.
  - **Derivative** - Derivative error correction is based on the rate of change of the error and takes into account future expectations. It is used in so called "Predictive Controllers". The first derivative of the error over time is calculated, and multiplied by another (negative) constant **D** , and also added to the controlled quantity. The derivative term provides a rapid response to a change in the system.

  Combinations of all three methods of error processing are often used simultaneously in "PID" controllers to address different system performance priorities. Where noise may be a problem, the derivative term is not used.

  PID controllers are also called "3 term controllers".

Motor controllers may be simple open loop systems or they may incorporate several nested closed loop systems operating simultaneously. For example closed loop controls may be used to synchronise the excitation of the stator poles with the angular position of the rotor or simply to control motor speed or the angular position of the rotor.

History

- **Four Quadrant Operation**

  When an electrical machine is required to work as both a motor and a generator in both forward and reverse directions this is said to be four quadrant operation. A simple motor which only runs in one direction and is never driven as a generator is an example of a single quadrant application. A motor designed for automotive use which must run in forward and reverse directions and which must provide regenerative braking in both directions needs a four quadrant controller.

  Control systems for four quadrant applications will obviously be more complex than single quadrant controls.

Basic Motor Control Functions and Applications

Controllers may have some or all of the following functions many of which have been implemented in integrated circuits.

- **Speed Control**
  - DC machines

    One of the major attractions of brushed DC motors is the simplicity of the controls. The speed is proportional to the voltage and the torque is proportional to the current.

    Speed control in brushed DC motors used to be accomplished by varying the supply voltage using lossy rheostats to drop the voltage. The speed of shunt wound DC motors can also be controlled by field weakening. Nowadays electronic voltage control is employed. See below.

    Simple open loop voltage control is sufficient when the motor has a fixed load, however open loop voltage control can not respond to changes in the load on the motor. If the load changes, the motor speed will also change. If the load is increased, the motor must deliver more torque to reach an equilibrium position and this needs more current. The motor consequently slows down, reducing the back EMF so that more current flows. To maintain the desired speed, a change in the voltage is needed to provide the necessary current required by the new load conditions. Automatic control of the speed can only be accomplished in a closed loop system. This uses a tachogenerator on the output shaft to feedback a measure of the actual speed. When this is compared with the desired speed, a "speed error" signal is generated which is used to change the input voltage to the motor to drive it towards the desired speed. Note - This is essentially a voltage control system since the tachogenerator usually provides a DC voltage output which is compared with a reference input voltage.

    Voltage control alone may be insufficient to cater for wide, fast changing load conditions on the motor since the voltage controller may call for currents in excess of the motor's design limits. A separate current feedback loop may be required to provide automatic current control. The current control loop must be nested within the voltage control loop. This allows the voltage control loop to deliver more current but it can not override the current control which ensures that the current remains within the limits set by the current control loop.

Brushless DC motors are powered by a pulsed DC supply to create a rotating field and the speed is synchronous with the frequency of the rotating field. Speed is controlled by varying the supply frequency. See Inverters below.

  - AC machines

    The speed of AC motors generally depends on the frequency of the supply voltage and the number of magnetic poles per phase in the stator. Early speed controllers depended on switching in different numbers of poles and control was only available manually and in crude steps. Modern electronic inverters make continuously variable frequency supplies possible permitting closed loop speed control. For speed control in induction motors however the supply voltage must change in unison with the frequency. This requires a special Volts/Hertz controller.

- **Torque Control**

  If the application requires direct control over the motor torque rather than the speed, in simple machines this can be accomplished by controlling the current, which is proportional to the torque, and omitting the speed control loop. For more precise control, vector controllers are used.

- **Voltage Control**

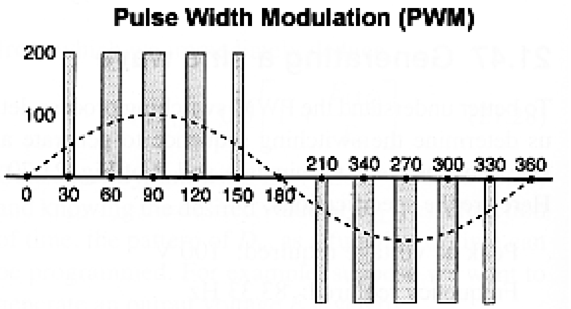
  It is no longer necessary to use energy wasting rheostats to provide a variable voltage.

  - **Voltage Choppers**

    Modern controllers use switching regulators or chopper circuits to provide a variable DC voltage from a fixed DC supply. The DC supply is switched on and off at high frequency (typically 10 kHz or more) using electronic switching devices such as MOSFETs, IGBTs or GTOs to provide a pulsed DC wave form. The average level of the output voltage can be controlled by varying the duty cycle of the chopper.

  - **Pulse Width Modulation (PWM)**

    AC voltages can be similarly controlled using bi-directional pulses to represent the sinusoidal wave.



Various PWM schemes are possible. Only one is shown here. By varying the pulse width, the amplitude of the sine wave can be changed.

Variable voltages can also be generated by using fixed pulse widths but by varying instead the pulse amplitude (Pulse Amplitude Modulation - PAM) or the pulse repetition frequency (Pulse Frequency Modulation - PFM).

The DC output from choppers and PWM circuits is notoriously plagued by high harmonic content. Most DC motors however can tolerate a pulsed DC supply since the inductance of the motor itself and the mechanical inertia of the rotor help to smooth out the variations in the supply voltage. Since there is no current flowing when the switching device is off, the technique is relatively loss free. Cogging may occur if the chopper frequency is too low.

The voltage controller may be activated manually in an open loop system but for continuous voltage control, the inverter must be incorporated into a feedback loop in a closed loop system. The control system monitors the actual output voltage and provides a control signal, which may be an analogue or digital representation of the error signal, to the pulse width modulator to correct any deviations. When voltage control is used for speed control the error signal may be derived from a tachogenerator on the motor output shaft.

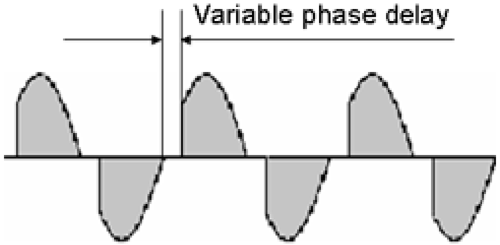
Electronic voltage control is also an essential part of many generator applications. In automotive systems the generator or alternator is driven at a variable speed which depends directly on the engine speed. It must give its full voltage output at the lowest speed but the voltage must be maintained as the engine speed rises. Alternators used in 12 Volt systems usually have built in voltage regulation. In HEV applications a chopper regulator is used at the output of the generator to maintain the voltage at the DC link within strict limits to avoid damaging the battery. When the battery is fully charged, the battery's own management system disconnects it from the supply to prevent overcharging.

- **Linear Voltage Regulators**

  For low power applications a series or linear regulator is often used. It is less efficient than a switching regulator since the variations in voltage must be taken up, and the associated power dissipated, by the volt dropping series transistor but it provides a pure DC. Series regulators are not suitable for high power applications such as electric traction where efficiency is paramount.

- **Thyristor Voltage Control**

  With AC supplies, Thyristors (SCR)s can be used in series with the load to create a variable voltage by blocking the passage of current to the load for the initial part of the cycle and turning the current on by applying a signal to the gate of the SCR. A single SCR only affects one polarity of the waveform. To switch both the positive and negative going current requires two SCRs connected in parallel and in opposite polarity or a triac (bidirectional SCR). By varying the delay (the phase angle) before the current is turned on, the average current, and thus the average voltage seen by the load, can be varied as shown below.



SCR Voltage Control

  This is the same principle as used in light dimmer switches.

  Gate turn off thyristors (GTOs) can be used to switch off the current as well as switching it on allowing more control over the duration of the current through the device.

- **Current Control**

  In many motor applications the motor current may lag the supply voltage due to the inductance in the circuit and it is often desirable to control the current directly, rather than the voltage, to obtain more precise or faster control of the current and hence the torque. In this case a shunt resistor or a current transformer is used to monitor the current. The difference between the actual and reference currents is used in a high gain feedback loop to provide the necessary current regulation.
- Current control is particularly important for induction motors to protect the motor from excessive start up currents. A current feedback signal is used to change the firing angle of thyristors in the rectifier or inverter circuits to limit the current within its reference value.

- **Converters**

  This a generic term for circuits which may provide AC or DC outputs from either AC (mains frequency) or DC (battery) supply lines. They include power bridges for rectifying the AC supply and inverters for generating an AC waveform from a battery supply.
  - **Buck and Boost Converters**

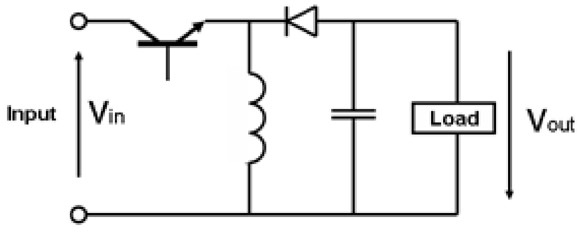
Buck and boost converters are DC-DC converters, the DC equivalent of AC transformers.

- **Buck Converter**

  The buck converter is used to reduce the DC voltage. The chopper above is an example of a step down DC converter.
- **Boost Converter**

  The boost converter is used to step up the DC voltage.

The circuit below can step up or step down the input voltage by varying the duty cycle of the transistor switch.



Buck – Boost Converter

The transistor switch turns the supply voltage to the LC circuit on and off. When the transistor is on, the inductor is charged up and the diode cuts off the capacitor. When the transistor turns off, the inductor discharges, via the diode, through the capacitor charging it up. Note that the polarity of the output voltage is the reverse of the input voltage. With a low duty cycle when the transistor is off more than 50% of the time, the voltage which appears at the output is lower than the supply voltage and the circuit acts as a step down transformer. With a high duty cycle when the transistor is switched on more than it is off, the voltage builds up on the capacitor and the output voltage exceeds the supply voltage. Voltage regulation is thus provided by varying the duty cycle.

- **Inverters**

  Inverters provide a controlled alternating current (AC) supply from a DC or AC source. There are two main classes of applications:
  - **Providing a fixed output from a variable source**

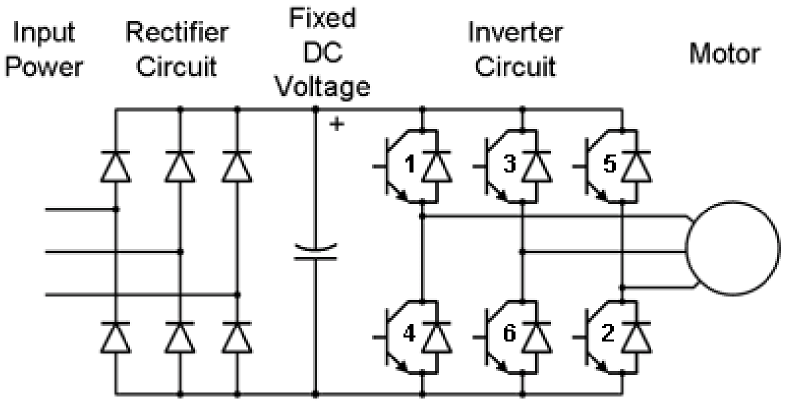
    Inverters designed to deliver regulated AC mains power from sources which may have a variable input voltage (either AC or DC) or in the case of AC input power, a variable frequency input. Such applications may include emergency generating sets, uninterruptible power supplies (UPS) or distributed power generation from wind and other intermittent resources. All must deliver a fixed output voltage and frequency to the load since the applications expect it and may depend on it.
  - **Providing a variable output from a fixed source**

    On the other hand, many applications require inverters to accept a fixed AC voltage and frequency from the mains and to provide a different or variable voltage and frequency for applications such as motor speed control. .

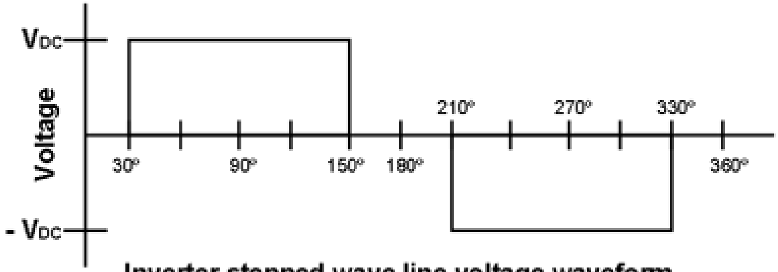
In both of these designs, a bridge rectifier is used to provide the intermediate DC power through a "DC Link" to a regular AC inverter.

The circuit below shows the principle of such an inverter designed for three phase applications.

Three phase variable frequency inverter



The three phase sinusoidal input is fed to a simple diode full wave bridge rectifier block delivering a fixed voltage to the inverter. The connection between the rectifier and the inverter is known as the DC Link. The inverter transistors are switched on in the sequence of their numbers as shown in the diagram with a time difference if T/6 and each transistor is kept on for a duration of T/4 where T is the time period for each complete cycle. The output line voltage wave form for each phase is shown below.



Inverter stepped wave line voltage waveform

This inverter frequency reference may simply be a voltage applied to the input of a Voltage Controlled Oscillator (VCO) examples of which are commonly available as integrated circuit chips, or it may be derived from a microprocessor clock. Digital logic circuits are used to derive the timed trigger pulses to the inverter switches from the frequency reference source. In the case of generators delivering mains power, the frequency reference value will be fixed.

The amplitude of the output wave is determined by the level of the DC supply voltage to the inverter block but it can be varied by thyristor (SCR) control of the rectifier circuit to provide a variable voltage at the DC link.

Instead of transistor switches, the inverter may use MOSFETs, IGBTs or SCRs.
Free-wheeling diodes connected across the transistors protect them from reverse bias inductive surges due to motor field decay which results when the transistors turn off by providing free wheeling paths for the stored energy.

The waveforms for traction applications are often stepped waves rather than pure sinusoids since they are easier to generate and the motor itself smoothes out the wave.

Variable frequency inverters are used when variable speed control is required. The frequency of the wave is controlled by a variable frequency clock which initiates the pulses.
For speed control in AC machines the voltage and frequency must vary in unison. See AC motor speed control. In open loop systems the operating point is set by a speed reference and the equilibrium speed is determined by the load torque. A closed loop system allows a fixed speed to be set. This requires a tachogenerator to provide a feedback of the actual speed for comparison with the desired speed. If there is a difference, an error signal is generated to bring the actual speed into line with the reference speed by adjusting both the voltage and the frequency so as to eliminate the speed difference.

- **Volts/Hertz Control**

  Volts/Hertz control is needed for speed control of induction motors. In an open loop system the control system converts the desired speed to a frequency reference input to a variable frequency, variable voltage inverter. At the same time it multiplies the frequency reference by the Volts/Hertz characteristic ratio of the motor to provide the corresponding voltage reference to the inverter. Changing the speed reference will then cause the voltage and frequency outputs from the inverter to change in unison.

  In a closed loop system a speed feedback signal provided from a tachogenerator on the motor output shaft is used in the control loop to derive a speed error signal to drive a Volts/Hertz control function similar to the one outlined above.
  As with large DC motors, speed control is normally accompanied by current control.

- **Cycloconverter**

  The cycloconverter converts AC supply frequency directly to a variable frequency AC without the intermediate DC link stage.
  The system is complex and works by sampling the voltage of each phase of the AC supply and synthesising the desired output waveform by switching on to the load for the duration of the sampling period, the phase whose voltage is closest to the desired voltage at the instant of

sampling. The output waveform is severely distorted and the capability of induction motors to cope with the very high harmonic content limits the maximum frequency for which the system can be used.

Cycloconverters are only suitable for very low frequencies, up to 30% of the input frequency. They are used for low speed high power drives to eliminate the need for a gearbox in heavy rolling and crushing mills and in traction applications for trains and ships.

- **Vector Control - Flux or Field Oriented Control (FOC)**

  All motors need a magnetising current and a torque producing current. In a brushed DC motor, these two currents are fed to two different windings. The magnetising current is fed to the stator or field winding and the torque producing current is fed to the rotor winding. This allows independent control of both the stator and the rotor fields. However in brushless motors such as permanent magnet motors or induction motors it is not possible to control the rotor field directly since there are no connections to it. Because the parameters to be controlled can not be measured, their values must be derived from parameters which can be measured and controlled. The only input over which control is possible is the input current supplied to the stator.

  The actual stator current is the vector sum of two current vectors, the inductive (*phase delayed*) magnetising current vector producing the flux in the air gap and the *in phase*, torque producing, current. To change the torque we need to change the *in phase*, torque producing, current but because we want the air gap flux to remain constant at its optimum level, the magnetising current should also remain unchanged when the torque changes.

  Vector Control or Field Oriented Control is a method of independently varying the magnitude and phase of the stator current vectors to adapt to the instantaneous speed and torque demands on the motor.
  It enables parameters over which no direct control is possible to be changed by changing instead, parameters which can be measured and controlled.

  For many applications vector control is not necessary, but for precision control, optimum efficiency and fast response, control over the rotor field is needed and alternative methods of indirect control have been developed. Because of the low cost of computing power, vector control is being used in more and more brushless motor applications.

  - **Vector Control Summary**
    - **Objectives** Maximum current-to-torque power conversion, fast transient response, precise control of torque, speed and position.
    - **Requires** Rotating flux to be maintained at 90 degrees to the rotor flux.
    - **Inputs** Available information (status of stator voltages and currents and rotor position and/or speed).

- **Uses** Two independent control loops to provide control of the magnetising and torque producing current vectors.
- **Calculates Error** Mathematical transforms to analyse input signals from the stator and calculate any deviation from the desired conditions of the rotor.
- **Calculates Correction** Mathematical inverse transforms to convert the rotor error signal back into control signals to be applied to the stator to counteract the error.
- **Activates** A pulse width modulated (PWM) inverter providing power to the motor.
- **Produces** Stator input voltage waveforms of the correct amplitude, frequency and phase to effect the change.
- **Method 1 Direct Control** Uses position sensors and complex mathematical transforms
- **Method 2 Indirect Control** "Sensorless" Uses even more complex mathematical transforms
  (Both of the above methods use current sensors for current control of the stator windings)
- **Repeats** Samples status and provides control signals at 20 kHz to provide continuous control.
- **Additional Benefits** Low speed control, efficiency improvement, smaller motors.

The good news is that a detailed knowledge of the process involved is not necessary since most of these tasks are implemented in integrated circuits and incorporated into the motor design. But read on to find out how the overall system is used.

- **Transient Response**

  Despite its many advantages, the venerable induction motor is relatively slow to respond to changes in load conditions or user commands for changes in speed. This is mainly because the rotor current can not instantaneously follow the applied voltage due to the delay caused by the inductance of the motor's windings.

  During the transition period the flux amplitude and its angle with respect to the rotor must be maintained so that the desired torque can be developed.

  Torque also depends on the magnitude of the flux but this depends on the inductive component of the current and can not be changed instantaneously. In any case the flux density is set to its optimum point before saturation occurs.

  Vector control is a way of changing the in phase current vector without changing the inductive magnetising current vector so that the machine response time is not subject to inductive delay.

- **Efficiency**

  The inductive phase lag noted above also causes an instantaneous loss of torque and reduced efficiency because the torque producing flux from the stator is not acting at 90 electrical degrees to the rotor field.

The torque on the rotor of any motor is at its maximum when the magnetic field due to the rotor is at right angles to the field due to the stator. See Interactive Fields

The vector control system provides instantaneous adjustments to the stator currents to control the position of the rotor with respect to the moving flux wave thus avoiding losses due to phase lag.

- **Implementation**

  The two control methods outlined below each describe the processing of one sample of the motor status and how error correction occurs. They both involve considerable mathematical processing power. The motor however needs continuous real time control to regulate the speed and torque and this needs sampling rates of 20 kHz or more increasing the signal processing load dramatically. This task is well within the scope of Digital Signal Processors (DSPs), special purpose integrated circuits designed for computationally intensive applications.

  Once the motor has a computer on board other functions such as communications and the controller area network (CAN Bus) can be integrated with the motor controls.

  The vector control system is essentially an indirect system using information about the system gained from a knowledge of the stator voltages and currents and its position. Both the "direct" and "indirect" control methods referred to below indicate how the information about the rotor position is obtained.

  To obtain the necessary information about the stator currents in a three phase system it is only necessary to measure two of the three phase currents supplying the motor since the algebraic sum of the currents flowing in two windings must equal the current flowing out of the third winding.

  - **Direct control**

    This method uses a position sensor to determine the angular position of the rotating shaft. The angle between the rotor flux and the rotating flux wave is the sum of the angular position of the shaft and the slip angle which can be derived from the rotor current. The position error (deviation from 90 degrees) is a measure of the required torque producing component of the stator current. This signal can then be used as the basis for a conventional current control loop.

    The flux component of the stator current must be calculated from a mathematical model of the motor. A mathematical transform (Clarke-Park transformation) is carried out on the actual stator currents to derive a measure of the actual flux and a representation of the deviation from the desired value. The inverse transform is used to derive the corresponding error correcting signals to be applied to the input of a variable frequency inverter to generate the appropriate stator currents (amplitude, frequency and phase) to correct the error.

The mathematical transforms require accurate inputs on the mechanical and electrical characteristics of the machine which are often difficult to measure or estimate. Self learning adaptive control systems have come to the rescue to generate the necessary reference data from measurements of the actual performance.
The control algorithms must also take into account environmental conditions. For instance the motor winding resistance (and hence the L/R time constant of the motor) depends on the temperature and the affect of temperature changes needs to be incorporated into the model.

        - **Indirect - Sensorless Control**
          Sensorless control only refers to the elimination of the position sensor used in the scheme above. The control system may have several other sensors. The position information provided by the position sensor can also be derived from mathematical transforms on the stator currents and voltages just as the flux is in the direct system. Since the sensor adds physical complexity and cost to the machine, and since the cost of computing power is constantly reducing, replacement of the sensor by mathematical techniques is now economically justified.
          The sensorless control method can be used to control motor speed almost down to zero.

    - **Servo Systems**
      Many of the techniques involved in vector control are applicable to servo systems and consequently vector controlled system are replacing some of the traditional servo systems.

- **Ward Leonard Controller**
  The Ward Leonard speed controller provides a variable speed drive from the fixed voltage and frequency AC mains electric supply. It uses three machines, an AC induction motor driven at a fixed speed from the mains supply, driving a DC generator which in turn powers a shunt wound DC motor, usually of similar construction to the generator. The DC output from the generator is directly connected to the armature of the DC motor. The motor speed is adjusted by using a rheostat to adjust the excitation current in the field winding of the generator to vary the generator output voltage. Ward Leonard controllers can still be seen in passenger lifts (elevators) throughout the world as well as on electric cranes, winding gear in coal mines and industrial process machinery though they have now largely been superceded by thyristor speed controllers.

History

- **Position Control**

  Stepping motors are usually employed when accurate position control is required. Accurate positioning is possible with an open loop system by counting pulses applied to the motor. Potentiometers can be used to provide position feedback in closed loop systems but shaft encoders provide more precise travel feedback by counting pulses.
  When long distances to the target or many motor revolutions are involved, it may be desirable to speed up the motor during the travel. In this case speed control may be provided by a feedback loop.

- **Electronic Commutation**

  The function of the commutator is to change the direction of the motor energising current as alternate rotor poles pass the stator poles. In brushless DC motors, the mechanical commutator is eliminated and the energising current is provided by the stator coils. Commutation is carried out by electronic switches which reverse the stator current as alternate rotor poles pass by the stator poles. This requires a position sensor to feedback the angular position of the rotor shaft to the motor controller to enable it to switch the direction of the current when the rotor poles are in the correct position with respect to the stator poles.

- **Starting**

  Some motor designs are not self starting when the power is applied. Such problems are usually addressed by the machine designer using auxiliary windings or other methods and are usually not apparent to the user.

  One problem faced by the user however is that starting in many machines is accompanied by a very high inrush current which is potentially damaging to the motor or its power supply. Current control systems outlined above are used to overcome this problem.

- **Regenerative Braking**

  The battery can only capture the maximum regenerative braking energy if the regen volts are greater than the battery volts. With a DC motor this needs a variable DC - DC converter whose output is based on motor speed to convert high current low voltage pulses from low speed braking to high voltage low current pulses. The control system must also step down any regen voltage which exceeds the battery's upper charging voltage limit to avoid damaging the battery and it must dump any excess energy into a resistive load when the battery reaches its full state of charge (SOC) of 100% or the current reaches the battery's recommended charging current limit. This is particularly important for Lithium batteries.

  To capture regenerative braking energy from induction motors requires the synchronous speed to be reduced below the motor speed by reducing the supply frequency. See Generator Action.

- **Power Factor Correction**

  To avoid unnecessary losses, or to meet the acceptable load requirements of the energy supply utility, power factor correction is often required with induction motors, particularly for large machines or in installations running many machines.

  The most common power factor correction is by means of added capacitors however, under certain circumstances the motor controller can also be used for this purpose

  Under light load conditions the magnetising current in an induction motor is relatively high with respect to the load current causing a low power factor. (See Induction Motors). As the load is increased, the *in phase* load current increases with respect to the magnetising current thus improving (increasing) the power factor.

  The motor controller can be used to address the problem of low power factor in lightly loaded machines. If the supply voltage is reduced at light load levels, the air gap flux will be reduced accordingly and the current (and slip) will have to increase to produce the same torque. The effect is to increase the load current with respect to the magnetising current, reducing the current lag and increasing the power factor. Simple thyristor control of the supply voltage will be sufficient to provide the necessary voltage control to implement this scheme.

  This method of power factor control is only practical for lightly loaded machines. With heavily loaded machines the power factor is normally reasonably high and the effect of voltage control is not significant.

- **Protection**

  The control systems outlined above are also designed to ensure that the electrical machine does not exceed its design voltage and current limits. In addition the machine may incorporate several simple protection devices.

  If it overheats, a temperature sensor or thermistor will cause the power to be switched off or cooling systems to be switched on. If it exceeds a safe speed limit, a centrifugal switch will interrupt the current.

- **Sensors**

  Some examples of the many types of sensors used in motor control systems are given below.

  - **Current -**
    - Current shunt - Inexpensive, lossy.
    - Current transformer - Efficient, AC only - can not measure DC.
    - Hall effect sensor.
  - **Voltage** - A to D converters.
  - **Frequency** - Pulse counting.
  - **Phase** - Derived from time differences between measured and reference sources.

  - **Temperature** - Thermistors, thermocouples.
  - **Light** - Photoelectric and fibre optics.
  - **Magnetic flux** - Hall effect sensor.
  - **Position** - Linear and angular.
    - Optical encoders (based on a light source, a code wheel and an optical detector).
    - Pulse counters - Linear and angular displacements. Pulses may be magnetic or optical.
    - Potentiometers - Limited range, low accuracy.
  - **Speed** - Tachogenerators based on various principles.
    - Rotary DC generator - Provides a voltage output.
    - Pulse counters - Pulses may be magnetic or optical.
    - Centrifugal switch (Limit switch).
  - **Torque** - Usually derived from motor current.
  - **Time** - Microprocessor clock.

Practical Controllers

- Simple low cost, low power machines usually have simple open loop control systems. The common DC brushed motor for instance needs only a simple voltage controller for speed control and low cost, integrated circuit controllers are available for this purpose.
- Higher power machines however tend to use more complex closed loop controllers which are usually custom designed for each particular machine and often built into the machine itself.
- The electronic circuits in the motor controller must be able to handle the full motor power and this may be a limiting factor in the design of a drive train. The main influencing variable is the maximum peak output current, because this defines the cost of the power electronics for a given maximum voltage.

  It is often necessary to use liquid cooling to accommodate the high power levels demanded by the motor.
- Polyphase machines need one set of power and control circuits per phase. The cost of the controller often limits the number of practical motor phases to typically 3 or 4.
- Safety features also play a more important role in larger machines since in case of machine failure the potential for damage is greater.
- Inverters, converters and commutator circuits used in motor controllers all switch very high currents are thus likely to be a source of Radio Frequency Interference (RFI).

  The system designer should also be aware of the consequences that high frequency, high current pulsed loads of the inverters and choppers may have on battery lifetime in DC traction systems such as hybrid electric vehicles. Similarly the voltage regulation of the on board generator and the regenerative braking charge pulses can also affect the battery adversely if not properly controlled.

Electric Machine Fundamentals

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International Standards and Testing Applicable to Batteries

> "The great thing about standards is that there are so many to choose from." - Anon.

Below are listed some of the most common standards applicable to battery applications and some of the organisations who issue them and or carry out quality assurance and conformance testing. In Europe, European standards are gradually being adopted in replacement of the previous national standards. Copies of the relevant standards can be obtained directly from the issuing organisations or from public libraries.

Standards and Safety Testing Organisations

Published Standards

- General Standards
- Lithium Batteries
- Nickel Metal Hydride Batteries
- Nickel Cadmium Batteries
- Lead Acid Batteries
- Photovoltaic Batteries
- Safety Standards
- Automotive Batteries
- Aircraft Batteries
- Military Standards
- Radio Battery Standards
- Standby Power Systems Standards
- Software Standards
- EMC/RFI Standards
- Ingress Protection (IP) Standards
- Battery Monitoring Standards
- Recycling and Disposal Standards
- Other Related Electrical Standards
- Quality Standards

See also the International Telecommunications Union (ITU) for the importance of standards.

Standards Setting and Safety Testing Organisations	
Abbreviation	**Name**
AENOR	Asociación Española de Normalización y Certificación (Spain)
ANSI	American National Standards Institute sponsored by NEMA
AS	Australian Standard
ASE	Association Suisse des Electriciens (Swiss)
ASQC	American Society for Quality Control
ASTM	American Society for Testing and Materials
ATEX	Explosive Atmospheres (Safety directive)
BCI	Battery Council International (Publishes Automotive Battery Standards)
BS	British Standards
CARB	California Air Resources Board (Automotive Emission Standards)
CE	Conformance with EU directives
CEN	European Committee for Normalisation (Standards Committee)
CENELEC	European Committee for Electrotechnical Standardisation
CISPA	International Special Committee on Radio Interference
CODATA	Committee on Data for Science and Technology (Committee of ICSU)
CSA	Canadian Standards Association
DEF	Defence Standards (UK)
DEMKO	Danmarks Electriske Materielkontrol (Denmark)
DIN	Deutsches Institut für Normung (German Institute for Standardisation)
ECE	Economic Commission for Europe regulations.
EIA	Electronics Industry Association (USA)
EN	European Norms (Standards)
FCC	Federal Communications Commission (USA)
FIMKO	Finnish Electrical Inspectorate
FIPA	Foundation for Intelligent Physical Agents (Interoperability standards)
GB	Guo Biao = National Standard (People's Republic of China)
HSE	Health & Safety Executive (UK)

ICSU	International Council for Science
IEC	International Electrotechnical Commission
IEE	Institution of Electrical Engineers (UK)
IEEE	Institute of Electrical and Electronics Engineers (USA)
IMQ	Instituto Italiano del Marchio de Qualitá
IP	Ingress Protection
ISO	International Standards Organisation
JIS	Japanese Industrial Standard
KEMA	Keuring van Elektrotechnishe Materialen (Netherlands)
KIST	Korean Institute of Standards and Technology
MIL	Military Standards (USA)
MISRA	Motor Industry Software Reliability Association (UK)
MVEG	Motor Vehicle Emission Group (EU Emission standards)
NAMAS	National Measurement Accreditation Service (UK Calibration)
NEMA	National Electric Manufacturers Association (USA)
NEMKO	Norges Electriske Materiellkontroll (Norway)
NF	Norme Française (France)
NFPA	National Fire Protection Association (USA)
NIJ	National Institute of Justice (USA)
OSHA	US Department of Labor - Occupational Safety & Health Administration
OVE	Osterreichischer Verband für Elektrotechnik (Austria)
PowerNet	Automotive 42 Volt Battery Standard
RESNA	Rehabilitation Engineering & Assistive Technology Society of North America
SAE	Society of Automotive Engineers (USA)
SEMKO	Svenska Elektriska Materielcontrollanstalten (Sweden)
SEV	Schweitzerischer Elektrotechnische Verein (Swiss)
STANAG	NATO Standards Agreements
STRD	DTI Standards and Technical Regulations Directorate (UK)
TIA	Telecommunications Industry Association (USA)
TR	Technical Report (Used by IEC)
TÜV	TÜV Rheinland Group (TUV - Technical Inspection Asssociation)
UKAS	UK Accreditation Service (Assessment of test services)/(Calibration)

UL	Underwriters Laboratories Requirements (USA)
USABC	United States Advanced Battery Consortium
USNEC	United States National Electrical Code
UTE	Union Technique de l'Electriciteé (France)
VDE	Verband Deutscher Elektrotechniker (Germany)

General Battery Standards

Standard Number	**Title**
IEC 60050	International electrotechnical vocabulary. Chapter 486: Secondary cells and batteries.
IEC 60086-1, BS 387	Primary Batteries - General
IEC 60086-2, BS	Batteries - General
ANSI C18.1M	Portable Primary Cells and Batteries with Aqueous Electrolyte - General and Specifications
ANSI C18.2M	Portable Rechargeable Cells and Batteries - General and Specifications
ANSI C18.3M	Portable Lithium Primary Cells and Batteries - General and Specifications
UL 2054	Safety of Commercial and Household Battery Packs - Testing
IEEE 1625	Standard for Rechargeable Batteries for Mobile Computers
USNEC Article 480	Storage Batteries
ISO 9000	A series of quality management systems standards created by the ISO. They are not specific to products or services, but apply to the processes that create them.
ISO 9001: 2000	Model for quality assurance in design, development, production, installation and servicing.
ISO 14000	A series of environmental management systems standards created by the ISO.
ISO/IEC/EN 17025	General Requirements for the Competence of Calibration and Testing Laboratories

Lithium Battery Standards

Standard Number	**Title**
BS 2G 239:1992	Specification for primary active lithium batteries for use in aircraft
BS EN 60086-4:2000, IEC 60086-4:2000	Primary batteries. Safety standard for lithium batteries
BS EN 61960-1:2001, IEC 61960-1:2000	Secondary lithium cells and batteries for portable applications. Secondary lithium cells
BS EN 61960-2:2002, IEC 61960-2:2001	Secondary lithium cells and batteries for portable applications. Secondary lithium batteries
02/208497 DC	IEC 61960. Ed.1. Secondary cells and batteries containing alkaline or other non-acid electrolytes. Secondary lithium cells and batteries for portable applications

02/209100 DC	IEC 62281. Ed.1. Safety of primary and secondary lithium cells and batteries during transport
BS G 239:1987	Specification for primary active lithium batteries for use in aircraft
BS EN 60086-4:1996, IEC 60086-4:1996	Primary batteries. Safety standard for lithium batteries
UL 1642	Safety of Lithium-Ion Batteries - Testing
GB /T18287-2000	Chinese National Standard for Lithium Ion batteries for mobile phones
ST/SG/AC.10/27/ Add.2	United Nations recommendations on the transport of dangerous goods

Nickel Metal Hydride Battery Standards

Standard Number	Title
BS EN 61436:1998, IEC 61436:1998	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Sealed nickel-metal hydride rechargeable single cells
BS EN 61808:2001, IEC 61808:1999	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Sealed nickel-metal hydride button rechargeable single cells
BS EN 61951-2:2001, IEC 61951-2:2001	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Portable sealed rechargeable single cells. Nickel-metal hydride
BS EN 61951-2:2003	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Portable sealed rechargeable single cells. Nickel-metal hydride
96/216533 DC	IEC 1808. Sealed nickel-metal hydride button rechargeable single cells (IEC Document 21A/207/CD)
97/204158 DC	IEC 1441. Secondary cells and batteries containing alkaline or other non-acid electrolytes. User-replaceable batteries containing more than one sealed nickel-metal hydride rechargeable cell for consumer electronic applications (21A/212/CD)
00/246138 DC	BS EN 61436 Ed 2. Sealed nickel-metal hydride rechargeable single cells (IEC Document 21A/303/CD)
GB/T18288-2000	Chinese National Standard for Nickel Metal Hydride batteries for mobile phones

Nickel Cadmium Battery Standards

Standard Number	Title
BS EN 1175-1:1998	Safety of industrial trucks. Electrical requirements. General requirements for battery powered trucks
BS EN 2570:1996	Nickel-cadmium batteries. Technical specification
BS EN 2985:1996	Nickel-cadmium batteries of format A type
BS EN 2986:1996	Nickel-cadmium batteries of format B type
BS EN 2987:1996	Nickel-cadmium batteries of format C type
BS EN 2988:1996	Nickel-cadmium batteries of format D type

BS EN 2991:1996	Nickel-cadmium batteries of format E type
BS EN 2993:1996	Nickel-cadmium batteries of format F type
BS EN 60285:1995, IEC 60285:1993	Alkaline secondary cells and batteries. Sealed nickel-cadmium cylindrical rechargeable single cells
BS EN 60622:1996	Sealed nickel-cadmium prismatic rechargeable single cells
BS EN 60622:2003	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Sealed nickel-cadmium prismatic rechargeable single cells
BS EN 60623:1996, IEC 60623:1990	Vented nickel-cadmium prismatic rechargeable single cells
BS EN 60623:2001, IEC 60623:2001	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Vented nickel-cadmium prismatic rechargeable single cells
BS EN 60993:2002	Electrolyte for vented nickel-cadmium cells
BS EN 61150:1994, IEC 61150:1992	Alkaline secondary cells and batteries. Sealed nickel-cadmium rechargeable monobloc batteries in button cell design
BS EN 61440:1998, IEC 61440:1997	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Sealed nickel-cadmium small prismatic rechargeable single cells
BS EN 61951-1:2001, IEC 61951-1:2001	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Portable sealed rechargeable single cells. Nickel-cadmium
BS EN 61951-1:2003	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Portable sealed rechargeable single cells. Nickel-cadmium
BS EN 62259:2004	Secondary cells and batteries containing alkaline or other non-acid electrolytes. Nickel-cadmium prismatic secondary single cells with partial gas recombination
94/216281 DC	Guide to the equipment manufacturers and users of alkaline secondary cells and batteries on possible safety and health hazards. Part 1:Nickel-cadmium. (21A/163/CD)
96/203612 DC	IEC 1914. Technical report type 2. Alternative publication for vented nickel-cadmium prismatic rechargeable single cells (IEC Document 21A/186/CDV)
98/203520 DC	IEC 61959-1, ED.1. Mechanical tests for sealed portable alkaline secondary cells and batteries. Part 1. Secondary cells IEC DOCUMENT 21A/239/CD
01/202968 DC	BS EN 60285. Ed.4. Secondary cells and batteries containing alkaline or other non-acid electrolytes. Sealed nickel-cadmium cylindrical rechargeable single cells
BS 5932:1980	Specification for sealed nickel-cadmium cylindrical rechargeable single cells
BS 6115:1981	Specification for sealed nickel-cadmium prismatic rechargeable single cells

BS 6260:1982	Specification for open nickel-cadmium prismatic rechargeable single cells
BS 3G 205:1983	Specification for lead-acid and nickel-cadmium rechargeable batteries
GB/T18289-2000	Chinese National Standard for Nickel Cadmium batteries for mobile phones

Lead Acid Battery Standards

Standard Number	Title
IEC/TR3 61431:1995	Guide for use of monitor systems for lead-acid traction batteries
IEC/TR 62060:2001	Monitoring of lead-acid stationary batteries User guide
BS 3031:1996	Specification for sulfuric acid used in lead-acid batteries
BS 4974:1975	Specification for water for lead-acid batteries
BS 6133:1995	Code of practice for safe operation of lead-acid stationary batteries
BS 6287:1982	Code of practice for safe operation of traction batteries
BS 6290-2:1999	Lead-acid stationary cells and batteries. Specification for the high-performance Planté positive type
BS 6290-3:1999	Lead-acid stationary cells and batteries. Specification for the flat positive plate type
BS 6290-4:1997	Lead-acid stationary cells and batteries. Specification for classifying valve regulated types
BS 7481:1992	Code of practice for testing venting systems and shields for lead-acid starter batteries
BS 7483:1991	Specification for lead-acid batteries for the propulsion of light electric vehicles
BS 6G 205-1:1995	Secondary batteries for aircraft. Specification for lead-acid batteries
BS EN 50342:2001	Lead-acid starter batteries. General requirements, methods of test and numbering
BS EN 60095-2:1993	Lead-acid starter batteries. Dimensions of batteries and dimensions and marking of terminals
BS EN 60095-4:1993	Lead-acid starter batteries. Dimensions of batteries for heavy commercial vehicles
BS EN 60254-1:1997, IEC 60254-1:1997	Lead-acid traction batteries. General requirements and methods of test
BS EN 60254-2:1997	Lead-acid traction batteries. Dimensions of cells and terminals and marking of polarity on cells
BS EN 60896-1:1992, IEC 60896-1:1987	Stationary lead-acid batteries. General requirements and methods of test. Vented types
BS EN 60896-2:1996, IEC 60896-2:1995	Stationary lead-acid batteries. General requirements and methods of test. Valve regulated types
BS EN 60896-11:2003	Stationary lead-acid batteries. General requirements and methods of test. Vented types. General requirements and methods of tests
BS EN 61044:1993, IEC 61044:1990	Opportunity-charging of lead-acid traction batteries

BS EN 61056-1:1993, IEC 61056-1:1991	Portable lead-acid cells and batteries (valve-regulated types). General requirements, functional characteristics. Methods of test
BS EN 61056-1:2003	Portable lead-acid cells and batteries (valve-regulated types). General requirements, functional characteristics. Methods of test
BS EN 61056-2:1997, IEC 61056-2:1994	Portable lead-acid cells and batteries (valve-regulated types). Dimensions, terminals and markings
BS EN 61056-2:2003	Portable lead-acid cells and batteries (valve-regulated types). Dimensions, terminals and marking
BS EN 61429:1997, IEC 61429:1995	Marking of secondary cells and batteries with the international recycling symbol ISO 7000-1135
88/74677 DC	Aerospace series. Lead acid batteries for aircraft. General standard (prEN 3199)
99/200338 DC	Aircraft batteries. Part 1. General test requirements and performance levels (IEC document 21/466/CD)
00/201034 DC	BS EN 60896-1 Ed.2. Stationary lead-acid batteries. General requirements and methods of test. Part 1. Vented types (IEC Document 21/487/CD)
00/202302 DC	BS EN 60952-2, Ed.2. Aircraft batteries. Part 2. Design and construction requirements (IEC Document 21/509/CD)
00/202303 DC	BS EN 60952-3, Ed. 2. Aircraft batteries. Part 3. External electrical connectors (IEC Document 21/510/CD)
03/107988 DC	IEC 60254-1. Lead-acid traction batteries. Part 1. General requirements and methods of tests
BS 440:1964	Specification for stationary batteries (lead-acid Planté positive type) for general electrical purposes
BS 2550:1971	Specification for lead-acid traction batteries for battery electric vehicles and trucks
BS 2550:1983	Specification for lead-acid traction batteries
BS 3031:1972	Specification for sulphuric acid for use in lead-acid batteries
BS 3911:Part 1:1982	Lead-acid starter batteries for internal combustion engines. Specification for batteries requiring regular maintenance
BS 3911:Part 2:1987	Lead-acid starter batteries for internal combustion engines. Specification for maintenance-free and low-maintenance batteries
BS 4945:1973	Specification for miners' cap lamp assemblies (incorporating lead-acid type batteries)
BS 6133:1982	Code of practice for safe operation of lead-acid stationary cells and batteries
BS 6133:1985	Code of practice for safe operation of lead-acid stationary cells and batteries
BS 6290:Part 1:1983	Lead-acid stationary cells and batteries. Specification for general requirements
BS 6290-2:1984	Lead-acid stationary cells and batteries. Specification for lead-acid high performance Planté´ positive type
BS 6290-3:1986	Lead-acid stationary cells and batteries. Specification for lead-acid pasted positive plate type
BS 6290:Part 4:1987	Lead-acid stationary cells and batteries. Specification for lead-acid valve regulated sealed type

BS 6745:Part 1:1986	Portable lead-acid cells and batteries. Specification for performance, design and construction of valve regulated sealed type
BS AU 118:1965	Recommendations for the storage, shipment and maintenance of lead acid batteries for motor vehicles
BS 3G 205:1983	Specification for lead-acid and nickel-cadmium rechargeable batteries
BS 4G 205:Part 1:1987	Secondary batteries for aircraft. Specification for lead-acid batteries
BS 5G 205:Part 1:1990	Secondary batteries for aircraft. Specification for lead-acid batteries
BS EN 60095-1:1993	Lead-acid starter batteries. General requirements and methods of test

Photovoltaic Battery Standards

Standard Number	**Title**
IEC 61427:1999	Secondary cells for solar photovoltaic energy systems General requirements and test methods
99/240906 DC	BS EN 50314-1. Photovoltaic systems. Charge regulators. Part 1. Safety. Test requirements and procedures
99/240907 DC	BS EN 50314-2. Photovoltaic systems. Charge regulators. Part 2. EMC. Test requirements and procedures
99/240908 DC	BS EN 50314-3. Photovoltaic systems. Charge regulators. Part 3. Performance. Test requirements and procedures
99/240909 DC	BS EN 50315-1. Accumulators for use in photovoltaic systems. Part 1. Safety. Test requirements and procedures
99/240910 DC	BS EN 50315-2. Accumulators for use in photovoltaic systems. Part 1. Performance. Test requirements and procedures

Safety Standards

Standard Number	**Title**
IEC 61508	The IEC requirements for the functional safety of Electrical/Electronic/Programmable Electronic Safety Related Systems
BS EN 1175-1:1998	Safety of industrial trucks. Electrical requirements. General requirements for battery powered trucks
BS EN 45510-2-3:2000	Guide for the procurement of power station equipment. Electrical equipment. Stationary batteries and chargers
BS EN 50272-2:2001	Safety requirements for secondary batteries and battery installations. Stationary batteries
BS EN60950-1: 2002	Low Voltage Directive (Safety)
IEC/TR2 61430:1997	Test methods for determining the performance of devices designed for reducing explosion hazards - Lead-acid batteries
IEC62133:2002	Secondary batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made of them, for use in portable applications
IEC/TR2 61438:1996	Possible safety and health hazards in the use of alkaline secondary cells and batteries - Guide to equipment manufacturers and users
ANSI C18.2M	Safety Requirements for Portable Rechargeable Cells and Batteries

UL 2054	Safety Requirements for Household and Commercial Batteries
EN 45011	General requirements for bodies operating product certification schemes
EAS	The UK Electrotechnical Assessment Scheme (Electrical installation safety standards managed by the IEE)
BS 2754	Memorandum. Construction of electrical equipment for protection against electric shock
STRD Low Voltage Directive	The Electrical Equipment (Safety) Regulations 1994 SI 1994 No. 3260 Implementing Directive 73/23/EEC (The Low Voltage Directive - LVD)
IEC 479-1	Effects of current on human beings and livestock
IEEE 80 2000	IEEE Guide for Safety in AC Substation Grounding
HSG 85	HSE publication. Electricity at Work. Safe Working Practices
NFPA 70E-1995	Standard for Electrical Safety Requirements for Employee Workplaces
OSHA - 29 CFR 1910, Subpart S, Electrical	Electrical industry safe occupational working standards
ATEX Directive 94/9EC	Guidelines for equipment intended for use in potentially Explosive Atmospheres (ATEX)
EN70079	

Automotive Battery Standards

Standard Number	**Title**
QS 9000	The ISO 9000 derivative for suppliers to the automotive industry. Developed in the USA by Ford, General Motors and Daimler Chrysler
ISO/TS16949:2002	Updated Technical Specification aligning US and European automotive quality supply chain standards
IEC 61982-1	Test parameters
IEC 61982-2:2002	Dynamic discharge performance test and dynamic endurance test
IEC 61982-3:2001	Performance and life testing (traffic compatible, urban use vehicles)
ISO11898	Specification for the CAN Bus
ISO 9141(4)	Specification for the LIN Bus
SAE J240	Life Test for Automotive Storage Batteries
SAE J537	Storage Batteries
SAE J551	Performance levels and methods of measurement of electromagnetic radiation from vehicles and devices (30 to 1000 MHz)
SAE J1127	Battery Cable
SAE J1455	Recommended Environmental Practice for Heavy-Duty Trucks
SAE J1718	Measurement of Hydrogen Gas Emission From Battery-Powered Passenger Cars and Light Trucks During Battery Charging

SAE J1742	Connections for High Voltage On-Board Road Vehicle Electrical Wiring Harnesses-Test Methods and General Performance Requirements
SAE J1766	Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing (Work in progress)
SAE J1772	SAE Electric Vehicle Conductive Charge Coupler
SAE J1773	SAE Electric Vehicle Inductively Coupled Charging
SAE J1797	Recommended Practice for Packaging of Electric Vehicle Battery Modules
SAE J1798	Recommended Practice for Performance Rating of Electric Vehicle Battery Modules
SAE J1811	Power Cable Terminals
SAE J1939	The SAE specification for the CAN Bus
SAE J2185	Life Test for Heavy-Duty Storage Batteries
SAE J2288	Life Cycle Testing of Electric Vehicle Battery Modules
SAE J2289	Electric Drive Battery Pack System Functional Guidelines
SAE J2293	Energy Transfer System for Electric Vehicles
SAE J2344	Guidelines for Electric Vehicle Safety
SAE J2380	Vibration Testing of Electric Vehicle Batteries
SAE J2464	Electric Vehicle Battery Abuse Testing
SAE J2602	The SAE specification for the LIN Bus
PowerNet 42V	Automotive industry consortium standard for 42 Volt batteries
BCI Battery Technical Manual	Automotive Lead Acid battery test procedures
BCI Battery Service Manual	General information about manufacturing and using automotive batteries.
BCI Test Specifications	Small Deep Cycling Batteries, Deep Cycle Marine/RV Batteries, Batteries for Golf Cars, Floor Maintenance Machinery
ECE 100	Construction and functional safety requirements for battery electric vehicles
ECE-15	UN/EEC driving load profile (See Battery Load Testing)
EUDC	UN/EEC Extra Urban Driving Cycle
NEDC	New European Driving Cycle (Modified cold start - No warm up) Also called the MVEG-B test
FUDS	Federal Urban Driving Schedule (USABC Load profile)
SAE J227a/C and D	SAE Driving Schedules
DST	Dynamic Stress Test (USABC battery test schedule)
2004/104/EC	European EMC Automotive Regulation

Aircraft Battery Standards

Standard Number	Title
99/200338 DC	Aircraft batteries. Part 1. General test requirements and performance levels (IEC document 21/466/CD)
00/202302 DC	BS EN 60952-2, Ed.2. Aircraft batteries. Part 2. Design and construction requirements (IEC Document 21/509/CD)
00/202303 DC	BS EN 60952-3, Ed. 2. Aircraft batteries. Part 3. External electrical connectors (IEC Document 21/510/CD)

Military Standards for Batteries, Software, EMC/RFI, Safety & Quality

Standard Number	Title
DEF STAN 61-3	Generic specification for batteries, non-rechargeable, primary Replaced by DEF STAN 61-21
DEF STAN 61-9	Generic specification for batteries, rechargeable, secondary Replaced by DEF STAN 61-21
DEF STAN 61-17	Requirements for the selection of batteries for service equipment
DEF STAN 61-21	General specification for batteries. (Includes a long series of supplements for individual battery types) Replaces DEF STAN 61-3 and 61-9
DEF STAN 00-40	Reliability and Maintainability
DEF STAN 00-55	Requirements for Safety Related Software in defence equipment
DEF STAN 00-56	Safety Management Requirements for defence systems
DEF STAN 05-91	Quality System Requirements for Design/Development, Production and Installation.
DEF STAN 05-95	Quality System Requirements for the Design, Development, Supply and Maintenance of Software.
DEF STAN 05-97	Requirements for Deliverable Quality Plans.
DEF STAN 08-46	The Electric, Magnetic and Electromagnetic Environment.
DEF STAN 59-41	Electromagnetic Compatibility (EMC)
MIL-STD-461 D	Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility
MIL-STD-461 E	Requirements for the control of electromagnetic interference characteristics of subsystems and equipment
MIL-STD-462 D	Measurement of Electromagnetic Interference Characteristics

Radio Battery Standards

Standard Number	Title
EIA/TIA 603 1993	Land Mobile FM or PM Communications Equipment, Measurement and Performance Standard (Battery duty cycles)
NIJ Standard - 0211.01 1995	Rechargeable Batteries for Personal/Portable Transceivers

Standby Power Systems Standards

Standard Number	Title

ANSI/IEEE 450-2002	IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications
ANSI/IEEE 1184-1994	IEEE Recommended Guide for Selection and Sizing Batteries for Uninterruptible Power Supply, (UPS)
ANSI/IEEE 1188-1996	IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid (VRLA) Batteries for Stationary Applications
IEC 60896-1 1987	Stationary Battery Tests
BS 6290 1999	Stationary Battery Tests
IEC 62040-3	Standards for different UPS Topologies and Methods of Performance Measurement (**V** indicates a prestandard)
ENV 50091-3	
NFPA 111 1989	Standard for Stored Electrical Energy Emergency and Standby Power Systems

Software Standards

Standard Number	**Title**
ISO/IEC 12207	Standard for software life cycle processes
MISRA C 1998	Guidelines for the use of the C language in vehicle based software. Derived from IEC 61508 Functional Safety Standards (See above)
	See also Military Standards above

EMC/RFI Standards

Standard Number	**Title**
	See Military Standards above

Ingress Protection (IP) Standards

Standard Number	**Title**
ANSI/IEC 60529-2004	Degrees of Protection Provided by Enclosures (IP Code)

Battery Monitoring Standards

Standard Number	**Title**
IEC/TR 61431 1995	Guide for the use of monitor systems for lead-acid traction batteries
IEC/TR 62060 2001	Secondary cells and batteries - Monitoring of lead acid stationary batteries - User guide

Battery Recycling and Disposal Standards

Standard Number	**Title**
EEC Directive 91/157	Batteries and accumulators containing certain dangerous substances. (Currently being revised)
BS EN 61429:1997, IEC 61429:1995	Marking of secondary cells and batteries with the international recycling symbol ISO 7000-1135

Other Related Electrical Standards

Standard Number	**Title**
BS 7671:2001	The IEE Wiring Regulations (UK)
NFPA 70 1993	National Electrical Code (USA)
UL 1310	Safety of Class 2 Power Supplies, AC Adapters and Battery Chargers - Testing
ISO 7176-4 1997 **ANSI/RESNA WC04**	Wheelchairs -- Part 4: Energy consumption of electric wheelchairs and scooters for determination of theoretical distance range
BS EN 60598-2-22:1999	Luminaires. Particular requirements. Luminaires for emergency lighting

Quality Standards

Standard Number	**Title**
ISO 9000:2000	Quality management systems. Fundamentals and vocabulary
ISO 14001:1996	Environmental management systems. Specification with guidance for use
ISO 2859-0:1995	Sampling procedures for inspection by attributes
ANSI/ASQC Z1.4	Sampling Procedures and Tables for Inspection by Attributes

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Battery Pack Design

The purpose of a battery pack is to provide a convenient integrated power source for portable applications. The advantages of using custom designs are outlined in the section on Benefits of Custom Packs. The pack may fulfil several functions:-

- It enables higher voltage or higher capacity batteries to be built up from low voltage, low capacity cells.
- It houses a cell or a bank of cells together with the associated interconnections in a single convenient pack.
- It accommodates any necessary monitoring and electronic protection devices or circuits within the pack.
- It can accommodate additional circuitry such as indicator lights, heaters, cooling ducts and solar panels.
- It matches and meshes with the cavity in the product which the battery is intended to power providing both electrical and mechanical interfaces.
- It can provide unique electrical and mechanical interfaces to ensure compatibility both of the battery with the intended product and the charger with the battery.

Two examples of battery packs from Axeon Power are shown below.

The pack on the left is a 12 Volt 30 Ah Lithium Ion battery used for seismic instrumentation. It uses 32 pouch cells in a 4 series, 8 parallel configuration. The pack incorporates heaters which enable it to work down to -30°C and a solar panel which keeps the battery charged.

The pack on the right is a 3.6 Volt 800 mAh battery employing three Nickel Metal Hydride cells used in mobile phones. The gold plated connector is moulded into the plastic frame.

See also Cell Construction

Capacity and Voltage

With a simple series chain of cells, the battery capacity in AmpHours is the same as the capacity of the individual cells since the current flows equally through all the cells in the chain.

High battery voltages are achieved by adding more cells in a series chain. The voltage of the battery is the voltage of a single cell multiplied by the number of cells in the chain. This does not increase the AmpHour capacity of the battery , but it increases the WattHour capacity, or the total stored energy, in proportion to the number of cells in the chain.

Battery capacity can increased through adding more parallel cells. This increases the AmpHour capacity as well as the WattHour capacity without increasing the battery voltage. For batteries with parallel chains the capacity of the battery is the capacity of the individual chain multiplied by the number of parallel chains.

Whereas cell voltage is fixed by the cell chemistry, cell capacity depends on the surface area of the electrodes and the volume of the electrolyte, - that is, the physical size of the cell. If at all possible the number of cells in a pack should be minimised to simplify the design and to minimise potential reliability problems. Fewer cells require fewer support electronics. Thus parallel chains should be avoided by specifying the highest capacity cells available. Design issues for multi-cell batteries are considered further in the section on Cell Balancing.

NOTE Cells with different capacities or cell chemistries should not be mixed in a single battery pack.

Pack Design Options

The design of the outer package or housing of the battery depends to a great extent on the components it has to accommodate and the physical protection it has to provide for them. These components are not just the cells, but also protection devices, electronic circuits, interconnections and connectors which must all be specified before the final battery case can be designed. For high power, high energy batteries robust packaging is required for safety reasons.

Cell Configuration

The ultimate shape and dimensions of the battery pack are mostly governed by the cavity which is planned to house it within the intended application. This in turn dictates the possible cell sizes and layouts which can be used. Prismatic cells provide the best space utilisation, however cylindrical cells provide simpler cooling options for high power batteries. The use of pouch cells provides the product designer more freedom in specifying the shape of the battery cavity permitting very compact designs.
The orientation of the cells is designed to minimise the interconnections between t he cells.

Battery Electronics

Besides the cells many battery packs now incorporate associated electronic circuits. These may be protection devices and circuits, monitoring circuits, charge controllers, fuel gauges, and indicator lights. Electronics for high power multi-cell packs also include cell balancing and communications functions.

The packs may also be designed to deliver more than one voltage from the basic cell combination, although applications requiring multiple voltage sources are more likely to make provision for this within the application. See Multiple Voltages

In addition to the basic battery support electronics the battery pack may include other functions such as heaters to extend the lower working temperature or solar cells to keep the battery fully charged. These circuits in turn have their own control circuits.

Space, fixing points and methods and interconnections need to be allocated for all these electronic circuits.

Software

Sofware is a major component of Lithium batteries, particularly for automotive applications. See the section on Battery Management Systems (BMS) . Control systems are required to keep the cells within their specified operating range and to protect them from abuse. Fuel gauging needs complex algorithms to estimate the state of charge (SOC). Communications with other vehicle systems are needed for monitoring the battery status and controlling energy flows.

Internal Interconnections

Low power cells are usually connected together using nickel strips which are welded to the cell terminals or the case. Soldering is not recommended since the soldering process is apt to apply large, uncontrolled amounts of heat to the battery components which may damage the separators or the vents which are normally made of plastic. Modern computer controlled resistance welders allow much more precise control of the welding process, both limiting the amount of heat applied to the battery and localising the heat to a small desired area. Welding also provides a stronger, low resistance joint. The interconnecting strips often have complex shapes and profiles which may be stamped out of flat strip in a progressive die.

High power cells may use solid copper bus bars or braided straps.

The electronic components are usually mounted on a conventional printed circuit board (PCB).

Flexible PCBs may cost more than rigid PCBs but they can be used to reduce the overall product costs. Not only do they save weight and space but they also provide more packaging options and they simplify physical interconnections and assembly operations as well as eliminating the need for connectors. Connectors may in fact be specified to facilitate assembly and disassembly if the design requires that individual battery components need to be changed or serviced but there is usually a cost and reliability penalty associated with such designs.

External Connections

The type of terminals or connections to the external circuits depend on, the current to be carried, the frequency with which the battery may be connected and disconnected and the design of the design of the circuit to which the battery will be connected.

For low power circuits, gold plated contacts are the terminals of choice for connectors which are subject to frequent insertions. Gold is hard wearing, it has low contact resistance and doesn't oxidise. Flying leads with spade terminals or snap on studs are also used for low power applications. Metal tabs are also used on pouch cells.

Terminals for high power applications are usually threaded metal studs to ensure a reliable connection. Safety requirements on high voltage batteries may also dictate shrouded terminals to prevent accidental exposure of the operator to dangerous voltages or of the battery to short circuits. Keyed or terminals or connections are also advisable to prevent connection to incorrect chargers or loads.

Thermal Design

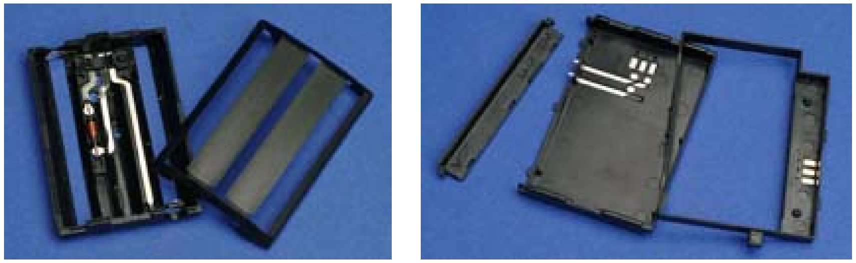
Thermal management is a major issue in high power designs, particularly for automotive applications. See details in the Thermal Management section. As part of the battery system, it may be necessary to provide air or water cooling ducts, pumps or fans and heat exchangers for high temperature working or heaters for operating in low temperature environments. The layout of the cells should be conducive to managing heat flows within the pack.

Battery Packaging

The battery casing has to provide the mechanical and electrical interfaces to the product it is designed to power as well as to contain all the components outlined above.

The simplest and least expensive packaging for small batteries is shrink wrap or vacuum formed plastic. These solutions are only possible if the battery is intended to be completely enclosed by the finished product.

Injection moulded plastics are used to provide more precision packs. For enclosed packs designs using a minimum of materials are based around which a plastic frame holds the components in place thus minimising the cost, the weight and the size of the pack. The overall product cost can be further reduced by using insert mouldings in which the interconnection strips and the terminals are moulded into the plastic parts to eliminate both materials and assembly costs. Overmoulding may also be used to encapsulate and protect small components or sub-assemblies.



Case for 3 AAA Cells **Case for a Single Prismatic Cell**

Insert Mouldings Showing Cell Interconnecting Strips

In some designs the battery pack forms part of the outer case of the end product. The colours and textures of the plastic must match the plastics of the rest of the product even though they may come from a completely different supplier. These designs are usually required to incorporate a mechanical latch to hold the battery in place. Again this latch as well as the terminals must interface with plastic parts from a different supplier so high precision and tight tolerances are essential. ABS polymers are the materials typically used for this purpose.

Batteries for traction applications are usually very large and heavy and subject to large physical forces as well as vibrations so substantial fixings are required to hold the cells in place. This is particularly necessary for batteries made up from pouch cells which are vulnerable to physical damage. Automotive battery packs must also withstand abuse and possible accidental damage so metal casings will normally be specified. The metal pack casing also serves to confine any incendiary event resulting from the failure of a cell or cells within the battery and to provide a measure of protection for the user. At the same time the case must also protect the cells and the electronics from the harsh operating environments of temperature extremes, water ingress, humidity and vibration in which these batteries work.

Usually the complete pack is replaced when the battery has reached the end of its useful life. In certain circumstances however, for instance when the pack incorporates a lot of electronic circuits, it may be desirable to design the pack such that the cells within the pack can be replaced.

14.4V 12Ah Lithium battery pack in an off-the-shelf case

If the design requires provision for replacement of the cells the casing of the battery pack must be designed to clip or screw together. Normally the parts of the plastic housing will be ultrasonically welded together both for security and for low cost as well as to prevent unauthorised tampering with the cells and the electronics.

Other Considerations

Thermal effects need to be taken into account and, tolerances must allow for potential swelling of the cells. Some Lithium pouch cells may swell as much as 10% or more over the lifetime of the cell. For this reason potting is not recommended. In low power designs groups of pouch cells may be shrink wrapped but for higher power applications plastic or metal frames may be used both to provide physical protection of the cells as well as to allow for swelling.

The battery pack should not normally be airtight or sealed since many batteries release hydrogen or oxygen during operation which could cause bursting of the pack or an explosion if the gases are allowed to accumulate. Lithium cells do not emit gases under normal circumstances, but in the case of failure and thermal breakdown, inflammable gases may be vented by the clells. Some form of ventilation or purging should be provided to avoid these problems.

Tolerances should also allow for the use of alternative cells from other manufacturers. While the cells may be "standard" sizes, there could still be differences between cells from different vendors.

High power batteries may need special ventilation or channels between the cells to permit forced air or liquid cooling.

Identification

The pack design must incorporate some form of identification to indicate the manufacturer's name, the cell chemistry, the voltage and the capacity as well as the country of manufacture. Most manufacturers will also include a date stamp and or serial number to assist traceability in case of problems. This information is usually provided on a label but it may also be printed directly on to the battery casing.

Pack Costs

The costs involved in designing custom battery packs are often underestimated.

As an indication of the order of magnitude, some very rough cost estimates are given below. They assume that the manufacturer posesses all the necessary standard production resources and they include the pack maker's profit margin and warranty provision. Costs could be lower if the packs are designed and made in house, but then some investment in capital equipment may be required and possibly some recruitment and training costs.

- **Design Engineering Costs**

  Low power batteries are usually designed for very high volume production and costs may be calculated to one thousandth of a cent. Most battery packs include some form of battery management electronics, even the smallest designs used in applications such as mobile phones incorporate integrated circuits mounted on a printed circuit board . The mechanical engineering effort however is the activity most often underestimated. It involves the design of precision thin section plastic parts and their associated complex moulding tools as well as metal stampings requiring precision stamping dies. Component sourcing as well as cell selection and qualification also add to the costs.

  For low power packs these engineering costs could amount to $20,000 to $50,000.

  High power batteries bring an additional set of challenges. Systems integration is much more complex due to the wider range of system functions and demands to be accommodated. For automotive applications the accuracy of the SOC estimation must be much higher and this may also require a major cell characterisation programme. The components are much larger and more expensive and the enormous energy content of the cells demands special safety considerations to prevent physical and electrical abuse and accidental damage. This requires robust steel frames and enclosures and fail safe electronics. Thermal management is also very important and designs may include both heating and forced cooling circuits. Expensive cable forms are needed to connect the cell voltage and temperature sensing signals to the BMS processing unit. All of these requirements add to the complexity, costs and timescales of the associated systems software.

  Enginering costs for EV and HEV applications could be upwards of $200,000 and probably much more.

- **Tooling Costs**

  High volume products may require multi-cavity moulding tools and progessive stamping dies. In addition automated transfer mechanisms and assembly jigs and fixtures will be required for the manufacturing operations.

  All this could cost a minimum of $100,000. This assumes the manufacturing plant is already equipped with standard engineering, production and test facilities such as CAD and CAM, PCB assembly machines, conveyer belts, welders, presses, power supplies and electrical test equipment.

  For manufacturing high power batteries, material handling and operator safety become major factors because of the heavy weight of the packs and the high voltages involved. Tooling costs may be double those needed for low power packs starting at $200,000 or more.

- **Prototypes**

  Prototypes could cost double the cost of volume production. Low volume purchases are more expensive and a considerable amount of manual work is involved. This is only significant for high power batteries.

- **Production Costs**

  The manufacturing costs for low power batteries used in mobile phones could be as low as $2.50 whereas a high capacity EV battery could cost upwards of $10,000. In both cases the major cost is the cells. In small batteries this may be 80% to 85% of the total costs. Large batteries use more electronics and higher power components. They are also more labour intensive. For large batteries the cost of the cells could be between 60% and 80% of the total costs depending on the battery specification. Since most cells are sourced from Asia, shipping costs also contribute significantly to the costs.

Two conclusions can be made from this .

- **Large production volumes are required to justify the development of custom battery packs.**
- **For safety reasons, batteries for electric vehicles involve very high unavoidable engineering development costs, even for a single vehicle.**

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PRODUCT DATA SHEET

The products referenced herein are exempt article and are not subject to OSHA's Hazard Communication Standard requirements for preparation of material safety data sheets. This information sheet is provided as a service to our customers.

Section 1- Product Information

Manufacturer
MPower Solutions Ltd
1 Nobel Court, Dundee
Scotland, DD2 4UH
Phone: +44(0)1382 400040
Fax: +44(0)1382 400044

Identity: Lithium Ion Batteries (Li-Ion)
Models: All
Date: November 12th 2004

Example MSDS for a Lithium Ion battery used in a mobile phone

Section 2- Material Ingredient Information

Important Note: The battery pack and enclosed cells should not be opened, disassembled, crushed, burned, or exposed to high temperatures (>60°C, 140°F). Exposure to the following ingredients contained within the battery could be harmful under some circumstances. In case of exposure to cell contents, wash affected area for at least 15 minutes with generous amounts of water and seek medical attention. Fires involving these types of battery packs should be flooded with water or use CO2, Foam or Dry Chemical extinguishing media.

MPower Battery Packs are composed of Li-Ion cells from various manufactures. Li-Ion cells are generally composed of the following ingredients:

Positive electrode:	Lithiated metal oxides (LiCoO2 or LiMn2O4)
Negative electrode:	Graphitic carbon
Binders:	Polyvinylidene difluoride and/or polytetrafluoroethylene
Electrolyte:	Lithium salt (lithium hexafluorophosphate) Organic solvents including one or more of the following: Ethylene carbonate, diethylcarbonate, dimethylcarbonate, ethylmethylcarbonate, and propylene carbonate.

Li-Ion cells are not manufactured to contain lithium metal.

Section 3

All MPower Li-Ion batteries contain recyclable materials. Recycling options available in your local area should be considered when disposing of this product. Do not dispose of in fire.

Section 4

MPower Li-Ion battery packs are not subject to the requirements of the U.S. Department of Transportation (DOT) subchapter C, Hazardous Material Regulations because these battery packs meet the exceptions under 173.185 (b). They are considered to be non-dangerous by the International Civil Aviation Organisation (ICAO) and the International Air Transport Association (IATA) because they meet all the requirements of Special Provision A45 as described by both organisations. They are considered to be non-dangerous by the International Maritime Dangerous Goods regulation (IMDG) because they meet the requirements of UN3090. They are considered non-dangerous because they meet the requirements of the UN directive ST/SG/AC.10/27/Add.2

The requirements for shipping these batteries, in all modes of transportation, are that they be separated from each other to prevent short-circuits and to prevent move,ment that could lead to short-circuits. Products must also be packed in strong packaging that can withstand the rigors normal to transportation. These products ae labels in accordance to Voluntary Air Transportation Communications Program (VATCP) for cargo shipments of Li-Ion batteries and cells.

__Notice:__ The information and recommendations set forth are made in good faith and are believed to be accurate at the date of preparation. MPower makes no warranty expressed or implied with respect to this information and recommendations and disclaims all liability from reliance on it. "Equivalent lithium content" information is available from MPower on request.

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Shocking Batteries

The vast majority of batteries are used in low voltage applications where there is little danger of electric shock, but familiarity can breed a careless attitude towards the potential dangers.

With high voltage batteries the danger of electric shock is very real.

As the use of batteries with voltages in excess of 300 Volts becomes more commonplace with the growing popularity of electric and hybrid electric vehicles, there is a danger that the general public, so used to relatively benign 12 Volt batteries, may underestimate the hazards associated with higher voltage traction batteries. Electric shocks account for about 1% of all fatal accidents, mostly to people who ought to know better.

This page describes the dangers and outlines some safety precautions when working with high voltage batteries.

Electric Shock

A physiologist may view the body as containing an electrical network, passing tiny nerve signals around enabling us to do all those essential things we like to do so much such as breathing, thinking and moving. Its function can be severely disrupted by the presence of an extraneous current. The body also contains a network of canals transporting oxygen to the muscles and the brain in a salty solvent called blood which incidentally provides a good conducting medium for electricity.

To the battery however, the body is an insulated skin bag containing electrolyte. See also **nerve impulses**.

Despite its common use as an indicator of danger, and the implication in the opening paragraph, voltage is not a reliable indicator of the severity of an electric shock. The most important indicators are the actual current which flows through the body and its duration, and even these can lead to misleading conclusions because the physiological consequences depend on the route the current takes through the body. Current passing through the heart or the brain is infinitely more damaging than current passing across a finger or the palm of the hand caught between the terminals of a battery. A sustained current will also do more damage than a short current pulse.

Physiological Consequences of Electric Shock

The table below outlines some of the effects of direct electrical currents passing through the body for a period of one second.

Important Notes: The two tables on this page are compiled from a variety of sources and although there is general agreement between the sources on the magnitude of the causes and effects, the actual values are subject to very wide variations. Obviously, it is not practical to perform tests on human subjects to verify the levels at which shocks become fatal and some data is derived test on animals. The values used are therefore average or typical values which should be used for illustrative purposes only.

Dangerous currents are shown in **Red**.

Shocking Effects

Current (contact 1 second)	Physiological Effect
Less than 1mA	No sensation
1mA	Threshold of feeling. Tingling sensation
5mA	Maximum harmless current
8 -15 mA	Mild shock Start of muscular contraction. No loss of muscular control
15 -20 mA	Painful shock Sustained muscular contraction. Can't let go of conductor
20-50 mA	Can't breathe. Paralysis of the chest muscles Possibly Fatal
50 - 100 mA	Intense pain Impaired breathing Ventricular fibrillation Possibly fatal - Fatal if continued
100-200 mA	Ventricular fibrillation Probably fatal - Fatal if continued Respiratory function continues
Over 200 mA	Sustained ventricular contractions followed by normal heart rhythm (defibrillation) Chest muscles clamp the heart and stop it for the duration of the shock. This also prevents ventricular fibrillation improving the chances of survival, but other factors come into play. Burns Temporary respiratory paralysis. Possibly fatal - Fatal if continued

Over 1 Amp	Severe burns. Internal organs burned. Death Survivable if vital organs not in current path - e.g. across a finger or hand

Notes:

- Low voltages do not mean low hazard.
- Other things being equal the degree of injury is proportional to the length of time the body is in the circuit.
- According to the IEEE Std. 80, the maximum safe duration of a shock can be determined by the formula

  T = 0.116/(E/R), where T is the time in seconds, E is the voltage and R, the resistance of the person (assumed to be 1000 ohms).

  For a 120V circuit the maximum shock duration = 0.116/(120V/1000) = 1 Second

  For a 240V circuit the maximum shock duration = 0.116/(240V/1000) = 0.5 Second
- It is extremely important to free a shock victim from contact with the current as quickly as possible. The difference of a few seconds in starting artificial respiration may spell life or death to the victim. Don't give up unless the victim has been pronounced dead by a doctor.
- Women tend to be more susceptible to electric currents than men
- Lower body weight increases the susceptibility to electric currents
- A shock from DC is more likely to freeze or stop the victim's heart.
- The current range of 100 to 200 ma, is particularly dangerous because it is almost certain to result in lethal ventricular fibrillation, the shocking of the heart into a useless flutter rather than a regular beat .
- The fibrillation threshold is a function of current over time. For example, fibrillation will occur with 500mA over 0.2 seconds or 75mA over 0.5 seconds.
- AC is more dangerous than DC causing more severe muscular contractions. AC is also more likely to cause a victim's heart to fibrillate , which is a more dangerous condition. Safe working thresholds are consequently much lower for AC voltages.
- It is easier to restart a stopped heart once the source of the electric shock has been removed than it is to restore a normal beating rhythm to a fibrillating heart. A heart that is in fibrillation cannot be restored to normal by closed chest cardiac massage. Defibrillators give the heart a jolt of DC to stop fibrillation to allow the heart to restart with a normal beat.
- Victims of a high voltage shock usually respond better to artificial respiration than do victims of a low voltage shock, probably because the higher voltage and current clamps the heart and hence prevents fibrillation. The chances of survival are good if the victim is given immediate attention.
- Shock victims may suffer heart trouble up to several hours after being shocked. The danger of electric shock does not end after the immediate medical attention.
- Don't expect a circuit breaker to protect you. They trip at 15 Amps.

Shocking Potential

While the severity of the electric shock is mainly determined by the current, the current in turn is influenced by numerous variables which make up the resistance of the current path making it difficult to predict the current which will flow from a given voltage. The two major components of the resistance are, the resistance of the body between the points of contact with the electrical circuit, and the contact resistance between the body and the voltage source. In more detail the body resistance depends on the length of the conducting path through the body and the body weight. The contact resistance depends on whether the contact is wet or dry, the area of the contact, the firmness of the grip or touch of the electrical contact and whether there is any other insulation in the path. Because of this wide variation in resistance and contact duration, people have been known to survive shocks of 40 KV while others have been killed by less than 50 Volts

The following table shows the conditions which could lead to a serious electric shock. It gives the body and contact resistances associated with a variety of conditions and indicates the current which will flow for different voltages. The table above outlines the consequences.

Currents Resulting From Electric Shocks

Circumstance	**Resistance** (Ohms)	**Current mA**			
		50V	**100V**	**250V**	**500V**
Hand to ground (Rubber gloves or soles)	20,000,000	0.002	0.005	0.01	0.02
Hand to ground (Dry hand, Leather soles)	1,000,000	0.05	0.1	0.2	0.5
Dry skin	500,000	0.1	0.2	0.5	1
Light touch (Dry)	500,000	0.1	0.2	0.5	1
Hand gripping wire or metal tool (Dry)	20,000	2.5	5	12.5	**25**
Light touch (Wet)	10,000	5	10	**25**	**50**
Hand to ground (Wet hand, Damp leather sole)	10,000	5	10	**25**	**50**
Hand gripping wire or metal tool (Wet)	5,000	10	**20**	**50**	**100**
Hand to Hand (Damp)	1500	**33.3**	**66.6**	**166**	**333**
Wet skin	1000	**50**	**100**	**250**	**500**
Across human body	1000	**50**	**100**	**250**	**500**
Hand to foot, Hand to hand (Excluding skin)	500	**100**	**200**	**500**	**1000**
Between the ears , Across a finger (Excluding skin)	100	**500**	**1000**	**2500**	**5000**

Punctured skin with cuts, abrasions or burns caused by the electric current itself	**No resistance**	**Very high**	**Very high**	**Very high**	**Very high**

Notes:

- The skin is a most important insulator.
- There are huge variations in contact resistance.
- Working with minor wounds to the hands seriously increases the risk of shock.
- Once a shock has been initiated, the resulting electrical burn can puncture the skin and increase the shocking current.
- Rings, bracelets and other jewellery decrease the contact resistance to the body and increase the potential for electric shock.
- Use only one hand (keeping one hand in your pocket) while working on high voltage circuits avoids the risk of the body becoming part of the circuit.
- Risks can be minimised by using insulated hand tools (pliers, screwdrivers, spanners etc.) and by wearing rubber gloves and shoes.

Safe Working Practices

There are many published standards for safe working practices on AC power circuits including those from the HSE in the UK and OSHA in the USA. See the section on Standards.

The following are additional recommendations relevant to working on battery circuits.

- The usual safe working voltage threshold for working on batteries is 50 volts DC.
- Avoid working on a fully charged battery. Arrange for batteries to be discharged wherever possible.
- Use a voltmeter to check whether the battery is charged before starting work.
- Check that any capacitors associated with the battery circuit are discharged.
- Cover exposed terminals where possible to avoid touching or dropping tools onto them.
- When starting work on a supposedly dead circuit make contact first with the back of one hand, so that if a shock should occur, the muscle reaction will not cause the hand to grip the conductor.
- See also the notes above.

Treat high power batteries with the same respect you would give to AC mains voltages.

See also Short Circuits and their Consequences

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Primary (Non Rechargeable) Batteries

Primary batteries are used once, then discarded. They have the advantage of convenience and cost less per battery, with the down side of costing more over the long term. Generally, primary batteries have a higher capacity and initial voltage than rechargeable batteries, and a sloping discharge curve . Most primary batteries do not presently require special disposal.

Advantages

High energy density since no design compromises necessary to accommodate recharging.

Best alternative for low cost, low drain applications such as watches or hearing aids.

The obvious choice for single use applications such as guided missiles and military ordnance.

Low initial cost

Convenient.

Wide availability of standard products

Shortcomings

Not suitable for high drain applications due to short life time and the cost of continuous replacement.

In terms of overall energy efficiency, single use, disposable, primary batteries are an extremely uneconomical energy source since they produce only about 2% of the power used in their manufacture.

They also produce much more waste than rechargeable batteries.

Applications

- Consumer batteries used in:-

  Toys
  Flashlights
  Watches
  Clocks
  Hearing aids
  Radios

- Specialist batteries used for:-

Implanted medical devices

Missiles

Weapons systems

See also Secondary Batteries

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Secondary (Rechargeable) Batteries

Secondary batteries are the rechargeable batteries. They have the advantage of being more cost-efficient over the long term, although individual batteries are more expensive. Generally, secondary batteries have a lower capacity and initial voltage, a flat discharge curve, higher self discharge rates and varying recharge life ratings. Secondary batteries usually have more active (less stable) chemistries which need special handling, containment and disposal. Ni-Cd and small-size lead acid batteries require special disposal and should not be simply thrown away.

Advantages

Best solution for high drain applications

For high utilisation applications the cost of the charger is soon paid back.

Shortcomings

Cost of charger. For low cost applications such as toys the charger could cost much more than the product it supports.

Safety issues with mains power.

Lower energy density than primary cells unless exotic chemistries used.

Lack of standards

Many custom pack designs and limited interchangeability. (Disadvantage for the user but creates a captive aftermarket for the manufacturer)

Applications

Traction

Power tools

Motor drives

Laptop computers

Mobile phones

PDAs

Camcorders

Toys

See also Primary Batteries

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Alkaline Batteries

Characteristics

Many battery chemistries use alkaline electrolytes but "Alkaline Batteries" usually refers to the **Alkaline Manganese Dioxide** primary cells described below.

1.5 Volt primary cell

Most popular premium general purpose battery.

In an alkaline cell the electrical energy is essentially derived from the reaction of a metal with oxygen.

The Alkaline Manganese Dioxide battery is a variant on the Leclanché cell. As with the Leclanché cell the electrodes are zinc and manganese dioxide but the electrolyte is potassium hydroxide (KOH). Potassium hydroxide is also used as the electrolyte in most of the Nickel based rechargeable cells.

Recently rechargeable cells using this chemistry have become available. Known as (RAM) Rechargeable Alkaline Manganese batteries they offer all the features and benefits of Alkaline primary cells, with the added benefit of being rechargeable, but without the disadvantage of "memory effect".

Advantages

Similar to, and interchangeable with, zinc carbon Leclanché cells but with as much as double the energy density.

Four times the capacity of a equivalent size rechargeable Nickel Cadmium or Nickel Metal Hydride cells.

Four to nine times longer life than the equivalent Leclanché cell.

Constant capacity over a wide range of current drains.

Suitable for high drain rate applications.

Good shelf life

Better low temperature performance than zinc carbon. Continue to function in sub-zero temperatures.

Less leakage than Leclanché cells

Available in a wide range of sizes including AAA, AA, C, D and 9Volt sizes.

Suitable for a wide range of consumer applications

Made from non toxic chemicals

Shortcomings

Higher cost than the basic competing zinc carbon Leclanché cells

Not normally rechargeable

25% heavier than Leclanché cells

RAM cells have limited cycle life of about 100 cycles and are only available in AA and AAA sizes.

Applications

Premium products

Toys

Remote controls

Flashlights

Clocks

Consumer applications

RAM cells can be interchanged with standard alkaline cells (but not mixed in the same application).

Costs

Low cost but about 50% higher than zinc carbon, however these cells are more cost effective because of the longer life.

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Cell Chemistry Comparison Chart

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Leclanché Cells

Characteristics

Primary cell with a nominal open circuit voltage of 1.5 Volts produced in very high volumes.

Chemistry based on a zinc anode and a cathode/depolariser of manganese dioxide which absorbs the liberated hydrogen bubbles which would otherwise insulate the electrode from the electrolyte. It uses a carbon rod as the cathode current collector with an electrolyte of ammonium chloride. Its variants have been in use for over a century. The performance of Leclanché cells improved by 700% between 1920 and 1990.

Also referred to as Zinc- Carbon Cells or Dry Cells (not to be confused with Solid State Cells) despite having an aqueous electrolyte since in modern cells the electrolyte of ammonium chloride and zinc chloride is produced in gel form or held in porous separators to reduce potential leakage if the cell becomes punctured.

Variants include

- Zinc carbon (Carbon cathode)
- Zinc chloride (Ammonium chloride electrolyte replaced by zinc chloride)
- Alkaline manganese (Ammonium chloride electrode replaced by potassium hydroxide)

See separate page for Alkaline batteries.

Advantages

Inexpensive materials

Low cost

Available in a wide range of sizes including AAA, AA, C, D and 9Volt sizes.

Suitable for a wide range of consumer applications

Interchangeable with alkaline batteries

Shortcomings

Propensity to leak

The basic zinc carbon battery has a lower energy density than the competing alkaline batteries

Poor low temperature performance. Do not function well in sub-zero temperatures.

The use of naturally occurring manganese dioxide from different sources can lead to wide performance variations due to the presence of small quantities of impurities such as nickel, copper, arsenic, and cobalt.

Not rechargeable

Applications

General purpose, low cost applications

Toys

Remote controls

Flashlights

Clocks

Consumer applications

Losing market share to alkaline cells and newer technologies

Costs

Lowest cost primary batteries

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Cell Chemistry Comparison Chart

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Traction Batteries for EV and HEV Applications

Battery Requirements for Typical Traction Applications

Traction applications have traditionally been jobs for Lead Acid batteries but the limitations of Lead Acid batteries, together with the high cost of alternatives, have in turn limited the range of potential battery powered traction applications. A typical family car would need a battery capacity of about 40 KWh to provide a one way range of 200 miles and a 40 KWh Lead Acid battery weighs 1.5 tons.

The situation is changing however as new battery chemistries and supporting technologies have brought with them new technical and economic benefits making battery power viable for traction applications that were previously uneconomic or impractical. In particular, the use of light weight Nickel Metal Hydride and Lithium batteries instead of the heavy and bulky Lead Acid batteries has made practical electric vehicles and hybrid electric vehicles possible for the first time.

General Requirements

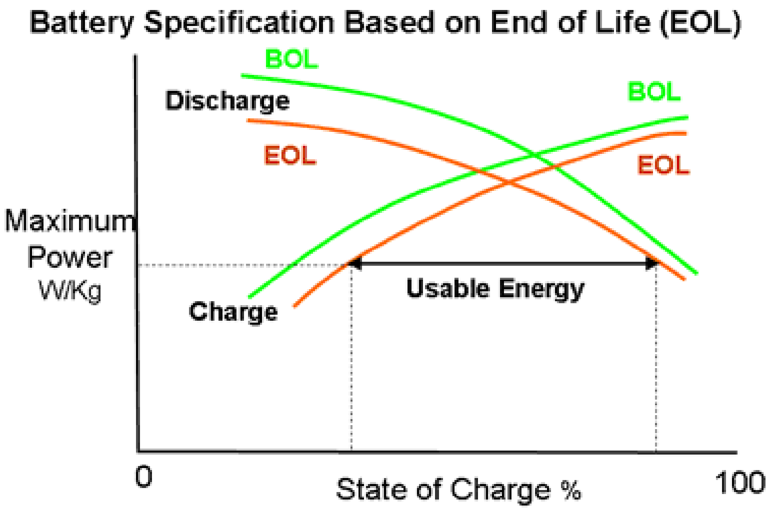
It goes without saying that low cost, long life (more than 1000 cycles), low self discharge rates (less than 5% per month) and low maintenance are basic requirements for all applications. Traction batteries generally operate in very harsh operating environments and must withstand wide temperature ranges (-30°C to +65°C) as well as shock, vibration and abuse. Low weight however is not always a priority since heavy weight provides stability for material handling equipment such as fork lift trucks and the grip needed by aircraft tugs for pulling heavy loads. Low weight is however essential for high capacity automotive EV and HEV batteries used in passenger vehicles and this rules out Lead Acid for these applications.

Protection circuits are also essential for batteries using non-Lead Acid chemistries.

Purchasing Speciications

Traction batteries are very expensive and like all batteries they deteriorate during their lifetime. Customers expect a minimum level of performance even at the end of the battery's life, so the buyer is likely to specify the expected performance at the end of life (EOL) rather than the beginning of life (BOL). Under normal circumstances for EV applications the EOL capacity is specified as not less than 80% of BOL capacity. For HEV applications change in internal impedance is often used as an indicator of lifetime. In this case the EOL internal impedance may be specified as not more than 200% of BOL internal impedance.

This is shown graphically below.



The following outlines the special performance goals and operating requirements for specific automotive applications in addition to the general requirements above.

12 Volt Automotive SLI (Starting, Lighting and Ignition) Battery Operating Requirements

- One short duration deep discharge (50% Depth of Discharge (DOD) with at least 5C rate) followed by trickle charging.
- Battery is essentially constantly fully charged.
- No prolonged operation with deep discharge.
- Typical capacity 0.4 - 1.2 kWh (33 Ah - 100Ah.)
- Peak power 2.4 -3.6 kW (200 - 300 Amps).

History

PowerNet 36/42 Volt Battery Operating Requirements

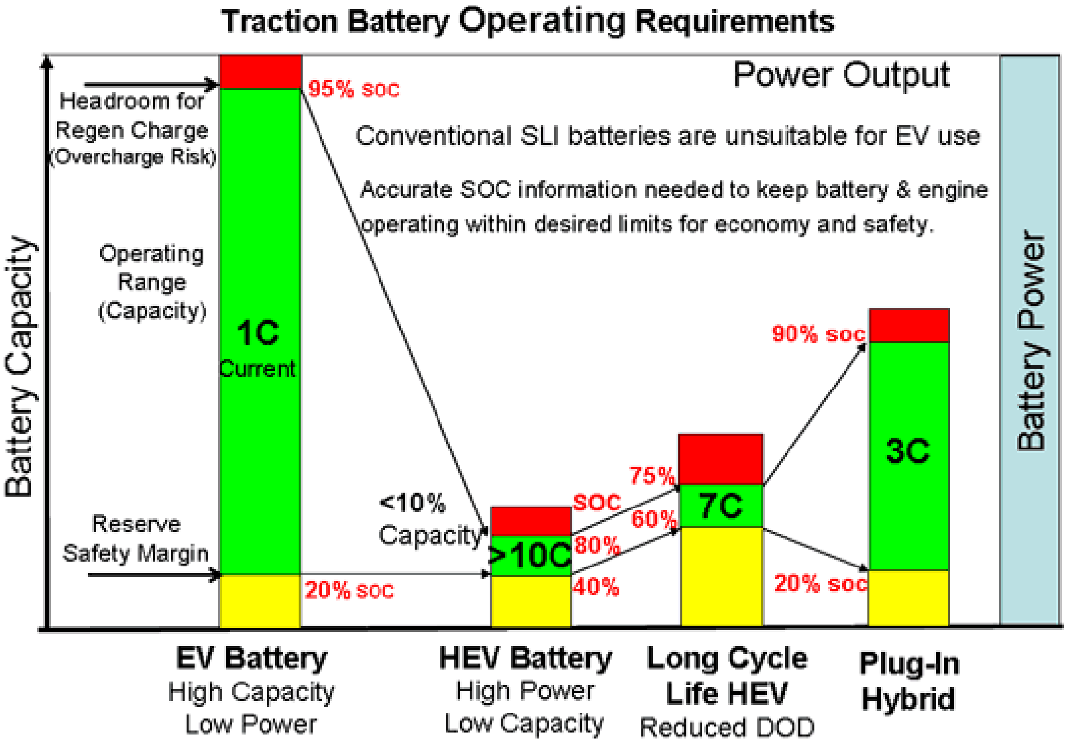
- One deep discharge followed by intermittent high current loads.
- No prolonged operation with deep discharge.
- High energy throughput and high cycle life essential, especially if stop/start launch assist function used.
- Tolerant to repeated high current pulses.are n
- Typical capacity over 1 kWh.
- Peak power 5 to12 kW.

History

The above two applications are not true traction applications though they may be used in mild hybrids which incorporate a start/stop mode (see below).

EV, HEV and PHV Battery Specifications

The diagram below compares the battery power and capacity requirements for a vehicle of the the same size and weight when configured as an EV, an HEV or a PHEV. Battery designs may be optimised for power or for capacity (energy content) but not both (see Energy/Power Tradeoffs in the section on Cell Construction) and so the type of cells used, not just the size, must be selected to suit the application.



In the case of the EV, the battery is the sole source of power so the battery must be sized to deliver that power on a more or less continuous basis. The EV capacity has to be sufficient to achieve the required range but in addition, since it is not desireable to fully discharge the battery, a margin of about 20% is needed so that the depth of discharge will not exceed 80%. A further margin of about 5% is also required the accept any regenerative braking charge when the battery has just been charged. In othe words the battery should dimensioned to provide the required capacity when the maximum SOC is 95% and the maximum DOD is 80%. The continuous discharge rate for batteries optimised for capacity is typically about 1C although some cells may tolerate pulse currents of up to 3C or more for short periods. An EV battery will usually have one deep discharge per day with some intermediate topping up from regen braking and a typical Lithium EV battery lifetime may be from 500 to 2000 cycles.

The battery for an equivalent series hybrid must also be able to deliver the same power as the EV battery because the vehicles are the essentially the same size and weight and for intermittent periods the battery will be the sole source of power. However, because the energy requirement is shared with an internal combustion engine (ICE) the battery capacity required is much smaller. Parallel hybrids may have different power sharing arrangements and so their power requirements could be accommodated by lower power batteries. HEVs thus have the added burden and complication of carrying around two power sources each of which is big enough to power the vehicle on its own.

The result is severe design constraints on the weight and size of the battery which can be accommodated and HEV batteries are typically less than one tenth the size of EV batteries used in the same size vehicle. The unavoidable consequence is that to get the same power out of a battery one tenth the size, HEV batteries must be capable of delivering continuous currents of 10C or more. Fortunately the power requirement is intermittent (but much longer than short pulsed demands) since it is shared with the ICE. Battery capacity is thus less important than power delivery in an HEV because the range can be extended by use of the engine. HEV batteries are therefore optimised for power.

The downside is that because of its low capacity, an HEV battery is continually being charged and discharged during normal operation and can undergo the equivalent of a hundred charge-discharge cycles per day. With deep discharges the battery would unfortunately be worn out in a few weeks. We know however that battery cycle life is increased exponentially as the the DOD is reduced (See Cycle Life and DOD in the section on Battery Life) so HEV batteries must be run at partial DOD in order to extend the cycle life. This means that the battery capacity must be increased accordingly to allow for lower DODs even though the full capacity is almost never used. In the example above the HEV battery operates between 40% and 80% SOC. Longer life can be achieved by using even larger capacity batteries so that the desired capacity can be delivered between SOC limits between 60% and 75%.

Plug in hybrids need to operate part of the time as an EV in the charge depletion mode and part of the time as an HEV in charge maintenance mode. See more detailed PHEV Requirements below. The PHEV battery requirement must therefore be a compromise between an energy storage and power delivery.

This is a major challenge for cell makers.

More detailed operating requirements are outlined below.

Electric Vehicle (EV) Battery Operating Requirements

Large capacity batteries are required to achieve reasonable range. A typical electric car uses around 150 to 250 Watt-hours per mile depending on the terrain and the driving style.

- The battery must be capable of regular deep discharge (80% DOD) operation
- It is designed to maximise energy content and deliver full power even with deep discharge to ensure long range.

- A range of capacities will be required to satisfy the needs of different sized vehicles and different usage patterns.
- Must accept very high repetitive pulsed charging currents (greater than 5C) if regenerative braking required.
- Without regenerative braking, controlled charging conditions and lower charging rates are possible. (At least 2C desirable).
- Routinely receives a full charge.
- Often also reaches nearly full discharge.
- Fuel-gauging critical near "empty" point.
- Needs a Battery Management System (BMS).
- Needs thermal management.
- Typical voltage > 300 Volts.
- Typical capacity > 20 - 60 kWh.
- Typical discharge current up to C rate continuous and 3 C peak for short durations.

Because these batteries are physically very large and heavy they need custom packaging to fit into the available space in the intended vehicle. Likewise the design layout and weight distribution of the pack must be integrated with the chassis design so as not to upset the vehicle dynamics. These mechanical requirements are particularly important for passenger cars.

History

Hybrid Electric Vehicle (HEV) Battery Operating Requirements

Capacity is less important with HEVs compared with EVs since the engine also provides capacity therefore the the battery can be much smaller, saving weight. However the battery may still be required to provide the same instantaneous power as the EV battery from time to time. This means that the smaller battery must deliver much higher currents when called upon.

A very wide range of batteries is required to accommodate the range of HEV configurations as well as vehicle performance requirements. Some examples are:

- **Series Hybrid** - The engine is used only to charge the battery. The electrical system provides a variable speed transmission and the electric motor provides the full driving power. Battery requirements similar to EV batteries but lower capacity needed since the charge is kept topped up by the engine.
- **Parallel Hybrid** - Both the engine and the electric motor provide power to the wheels. Various configurations possible to satisfy different operating conditions. The share of the load taken by the electric motor can range from zero to 100% depending on the operating conditions and the design goals. The battery capacity may be as low as 2 KWh but it must deliver short duration power boosts requiring very high currents of up to 40C for acceleration and hill climbing.

Some examples of different EV and HEV design goals which affect the battery specification are:

- **Efficiency Optimisation** - This allows the engine to run at its most efficient constant speed simply to keep the battery charged. The electrical drive eliminates the gearbox and provides the variable power output required. This type of drive was first used on Diesel Electric Locomotives. Improved efficiency reduces the fuel consumption which in turn automatically reduces exhaust emissions.
- **Efficiency Boost** - This uses the battery simply to capture the energy, which would otherwise be lost, from regenerative braking. The captured energy is used to provide a power boost for acceleration and hill climbing.
- **Range Extender** - This is basically an EV which uses the engine to top up the battery to prevent excessive depth of discharge.
- **Stop/Start Mode** - This allows the engine to be switched off to save fuel when the vehicle is temporarily stationary at traffic lights or in traffic jams etc. The vehicle moves off under battery power and the engine is restarted when a predetermined speed is reached.
- **Town and Country Mode** - This allows the vehicle to be used in EV mode while in town or in heavy traffic where it is most suited, and to be used as a normal internal combustion engined vehicle for high speed or long distance highway driving to avoid the range limitations of the EV.
- **Multi-mode** - Increased versatility is possible by using combinations of the above modes.
- **Capacity and Power** - In addition to the above operating modes, different batteries will be required to accommodate a range of performance requirements such as economy, top speed, acceleration, load carrying capacity, range and noxious emissions.

The battery has become an important product differentiator, just like the engine is.

Because of the very wide range of HEV operating requirements there are no standard batteries available to match the resulting range of specifications for battery voltage, capacity and power handling and batteries must be custom designed specifically for the intended application.

Some typical requirements are as follows:

- Designed to maximise power delivered.
- Must deliver high power (up to 40C) in repetitive shallow discharges and accept very high recharging rates.
- Very long cycle life 1000 deep cycles and 400,000 - 1,000,000 shallow cycles.
- Operating point is between 15% and 50% DOD to allow for regenerative braking.
- Never reaches full discharge.
- Rarely reaches full charge.
- Needs thermal management.
- Fuel-gauging and complex BMS necessary to regulate battery energy management as well as for driver instrumentation.
- Needs interfacing with overall vehicle energy management.
- Typical voltage > 144 Volts.
- Typical power > 40 kW (50 bhp).
- Capacity 1 to 10 kWh depending on the application.
- As with EVs above, the size, shape and weight distribution of the battery pack must be tailored to the vehicle.

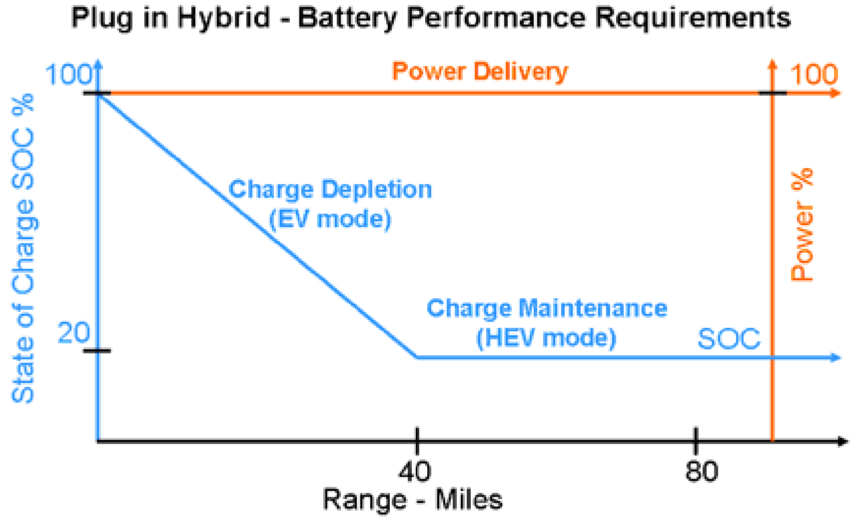
History

Plug in Hybrid Electric Vehicle (PHEV) Battery Operating Requirements

Batteries for plug in hybrid vehicles must satisfy conflicting performance requirements.

Traction batteries are usually optimised for high capacity in the case of pure electric vehicles of for high power in the case of hybrid vehicles. The EV battery operates down to a deep depth of discharge (DOD) for long range whereas the HEV operates at a shallow DOD for long life.

The plug in hybrid is designed to be used both as an EV for city driving and as an HEV when the charge is depleted or for highway driving. The dual requirements for an extended all electric range, typically forty miles, as well as maintaining high power availability at low state of charge, (see below), impose very stressful conditions on the battery.



The PHEV battery is thus expected to perform both as an EV and as an HEV.

The all electric range requirement can only be satisfied by using larger capacity batteries which adds considerably to the cost and because the high cost, consumers have high expectations about battery lifetime.

Bicycle Battery Operating Requirements

In China where the bicycle is a workhorse, batteries are typically 36 Volt units.

In Europe and USA where bicycles are more often used for recreation, lighter, 24 Volt batteries are more popular.

- Designed as removable modules for convenient indoor charging and as anti theft precaution.
- Should give 5 Amps for 2 hours (240 to 360 Wh depending on the voltage) to allow one hour travel to work. Higher capacity not feasible with Lead Acid because the weight puts limits on portability.

- Peak current 15 Amps.
- Long lifetime minimum 500 cycles or two years.

Marine Battery Operating Requirements

- Requires deep cycle batteries.
- Wide range of capacities and powers required.
- Low weight.
- Must be tolerant to wide range of charging conditions.
- Special environmental conditions.

Materials Handling Equipment Battery Operating Requirements

Similar to EV applications but normally no weight restrictions.

Practical Traction Batteries

For over a century Lead Acid batteries have been the prime source of energy for traction applications because they are both robust and relatively inexpensive. For fork lift trucks, milk floats and similar applications Nickel Iron batteries, which are almost indestructible and have a lifetime of up to ten years, have also been used successfully. The high weight and bulk of these batteries however has precluded their use in passenger cars.

In the 1970s work started on Sodium Nickel Chloride (Zebra) batteries designed for traction applications since they offer the possibility of very high energy densities which could overcome this problem. Unfortunately these are high temperature batteries which must run at 270°C and this has limited their adoption.

The advent of high power Nickel Metal Hydride (NiMH) cells which have overcome both the weight and the operating temperature problems has encouraged several automotive manufacturers to introduce EVs or HEVs using NiMH batteries. NiMH cells operate at normal ambient temperatures. They have a higher energy and power density than Lead Acid cells but not as good as the Zebra cells.

Recently high power Lithium Ion cells which have an even higher energy density than NiMH cells, on a par with Zebra cells, have become available. They also operate at normal temperatures and are just being introduced into new electric vehicle designs.
These new high energy cells however are more vulnerable to abuse and need the support of electronic Battery Management Systems to provide protection and ensure long cycle life.

Traction Battery Chargers

High capacity batteries also require high power chargers to achieve reasonable charging times and the chargers must be compatible with the cell chemistry and should be able to interface with the cell protection circuitry. Just as the battery is matched to the vehicle, the charger must be custom designed and matched to the battery. More information can be found in the section on Chargers.

Traction Applications - Electric Drives

Market Trends

Information on battery sales volumes and industry trends is given on the History pages.

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Homebrew Battery

For many years, before batteries were mass produced, electrical experimenters had to make their own batteries and many concoctions were tried.

You "can" try this at home yourself with materials commonly found around the house.

Recipe for Making a DIY Battery

Ingredients

- 1 Lemon or lime
- 1 Galvanised roofing nail or galvanised screw
- 1 Piece of heavy copper wire (Mains cable without the insulation) or a shiny copper coin.

Equipment needed

- 1 Voltmeter

Checking the Ingredients (Optional)

You could try the old fashioned "Tongue Test" (First make sure the parts are clean. See 2 below)

As with wine tasting: Taste - Don't swallow.

(**Note:** This is an experiment in electronics, not electric cooking. We recommend that you **do not eat the fruit** used in your battery)

Preparation

1. Squeeze the lemon gently without breaking the peel to release the juices inside.
2. Thoroughly clean the nail and the copper wire until they are bright. Use steel wool if necessary and rinse well in water.
3. Insert the nail and the copper wire deeply into two separate points on the lemon taking care that the wire does not touch the nail.
4. Check the potential between your two improvised skewers with the voltmeter.

Brewing time

Ready immediately

Serves up

About half a Volt

Hungry for Power?

Don't expect to start your car with this battery - The internal resistance is rather high.

By connecting 3 or 4 batteries in series however you should be able to light up an LED (Light Emitting Diode) or a small flashlight.

Flavours

The lemon may be replaced by other fruits or vegetables. You could try an Electric Potato for starters. The electric effect is the same.

Using a paper clip instead of the nail reduces the output to one third of a Volt.

If you can't find a galvanised nail, an alternative (and better) source of zinc is to cut a strip from the case of an old flashlight zinc carbon battery (D Cell).

Chef's notes

The lemon acts as a battery case holding the lemon juice (citric acid) which acts as the electrolyte. The copper **P**enny is the **P**ositive electrode and the zinc galvanised coating on the **N**ail is the **N**egative electrode.

A series connection is a chain of cells, the positive electrode of each cell connected to the negative electrode of the next cell, to form a battery of higher voltage.

Alternatives

A passable replica of **Volta's pile** can be constructed from a stack of alternately placed copper and nickel coins separated by discs cut from a paper towel and soaked in lemon juice or vinegar.

(Make sure the surfaces of the coins are not oxidised)

.

For an explanation of **how batteries work**, see Battery Chemistries.

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Zinc/Silver Oxide Batteries
Also called Silver Zinc Batteries

Characteristics

Common low capacity primary button cell versions are typically called **Silver Oxide** batteries. Higher capacity versions available as secondary cells are more often referred to as **Silver Zinc** batteries. They have an open circuit voltage of 1.6 Volts. Two types of Silver Oxide batteries are available, one type with a sodium hydroxide (NaOH) electrolyte and the other with a potassium hydroxide (KOH) electrolyte.

Because of the high cost of sliver they are available in either very small sizes as button cells where the amount of silver used is small and not a significant contributor to the overall product costs or they are available in very large sizes for critical applications where the superior performance characteristics of the silver oxide chemistry outweigh any cost considerations.

Advantages

High capacity per unit weight.

Long operating life. A tiny button cell will keep a watch running 24 hours per day for 3 to 5 years!!

Low self discharge and hence long shelf life (better than zinc air)

Better low temperature performance than zinc air

Flat discharge characteristics - flatter than the Alkaline Manganese Dioxide battery.

Higher voltage than zinc mercury cells..

Shortcomings

Uses expensive materials.

Lower energy density than zinc air.

Poor low temperature performance.

Limited cycle life.

Suffers from dissolving of the Zinc and the formation of Zinc dendrites which pierce the separator.

Applications

A major contribution to miniature power sources.

As a button cell it is well suited for hearing aids, instruments, photographic applications, electronic watches and other low power devices.

Larger size Silver Zinc batteries are used in submarines, missiles, underwater and aerospace applications.

Silver Zinc secondary cells being promoted as a safer alternative to Lithium cells. Plans to mitigate the higher costs by implementing a recycling programme.

Costs

More expensive than zinc air

Very expensive for high power applications

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Primary Lithium Cells

Characteristics

Lithium is the lightest of metals and it floats on water. It also has the greatest electrochemical potential which makes it one of the most reactive of metals. These properties give Lithium the potential to achieve very high energy and power densities permitting batteries with very long useful life and small cell packages.

Because Lithium reacts violently with water, as well as nitrogen in air, this requires sealed cells. High-rate Llithium cells build up temperature and pressure if they are short circuited or abused. Thus, the cell design needs to include safety vents, which release the pressure or rupture to prevent uncontrolled explosion.

Typical chemistries are Lithium Manganese dioxide, Lithium Sulphur dioxide, Lithium Thionyl Chloride (see below) and Lithium Oxygen (see below) but other variants are available.

Available cell voltages range between 3 and 4 Volts

Cell packaging includes coin cell and cylindrical packages.

Thin film cells based on ceramic or flexible substrates are also available.

Advantages

High energy density, double that of premium alkaline batteries

Low weight

High cell voltage

Flat discharge characteristic

Low self discharge

Very long shelf life

Very long operating life (15 to 20 years for lithium thionyl chloride)

Wide operating temperature range (-60 ° C to +85 ° C for lithium sulfur dioxide)

Excellent durability

Small cell size

Shortcomings

High cost

Applications

Computer memory protection

Medical implants

Heart pacemakers

Defibrillators

Utility meters

Watches

Cameras

Calculators

Car keys

Security transmitters

Smoke alarms

Aerospace applications

Because of its superior performance characteristics Lithium technology is replacing older, traditional technologies in an ever widening range of applications.

Costs

More expensive than common consumer primary Leclanché and alkaline batteries

Lithium-Manganese Dioxide Cell

Anode: Lithium foil cathode: Manganese dioxide electrolyte: separator sheet impregnated with electrolytic salts cell voltage: 3 volts The most common non-rechargeable Lithium cell.

Lithium Iron Disulphide Cell

Anode: Lithium foil cathode: Iron disulfide with Aluminium cathode contact electrolyte: separator sheet impregnated with electrolytic salts. Designed to be a drop in replacement for Zinc Carbon or alkaline batteries the cell voltage: 1.5 volts. Often called the "Voltage compatible" Lithium cell, they have a higher energy density than the cells they replace and tailored to high current applications.

Lithium Thionyl Chloride Cell

The highest energy density of all Lithium type cells have a service life of 15 to 20 years.

Lithium Iodine Cell

Provides excellent safety and long life. Uses only solid components and the separator is self healing if cracks occur. High internal impedance limits its use to low drain applications. Used for the majority of implanted cardiac pacemakers.

Lithium Air Cell

Similar to Zinc Air cells they have a very high theoretical energy density. The anode, a metallic Lithium foil pressed into a nickel mesh current collector, is electrochemically coupled to an unlimited supply of atmospheric Oxygen through an air cathode. The air cathode is a layered electrode with two Carbon layers containing catalysts, such as Manganese, separated by a Nickel mesh current collector. A PTFE Teflon membrane is used to repel water from the atmosphere while still allowing Oxygen diffusion. Non-aqueous electrolytes such as $LiPF_6$ must be used due to Lithium interaction with water

The cell voltage is 3.0 Volts and the storage capacity is limited by the Lithium anode. The cell has a flat discharge curve and a long storage life.

Performance varies widely wih temperature.

Rechargeable versions are also possible.

See note on the **Toxicity** of Lithium

History

See also Lithium secondary cells

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Water Activated Batteries

Characteristics

These are single use primary cells often called "reserve batteries" with a long shelf life used mainly for emergency applications.

Stored in the dry condition and activated at the time of use by adding or immersing in water or adding an aqueous electrolyte.

Seawater-activated types also available.

Magnesium is generally used as the anode material with various chlorides being used for the cathode cost being traded off for performance, silver chloride having superior energy and current density while while cuprous chloride has lower costs.

Aluminium anodes are also widely used with seawater-activated batteries.

Very high current densities possible.

Advantages

Reliable

Rugged

Safe

Light weight without the need to carry the electrolyte.

High power and energy densities

Good response to pulse loading

Instantaneous activation

Long unactivated shelf life

No maintenance

Shortcomings

High self discharge rate after activation

Once activated they must be replaced.

Applications

Military applications

Marine use for sonobuoys, life jackets, air sea rescue equipment, emergency lighting, weather balloons.

Forced flow types used for powering torpedoes can deliver over 300kW for 10 minutes

Costs

Silver cathode types have high material costs

Non-silver cathode types have low material costs

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Thermal Batteries

Characteristics

These are single use High Temperature galvanic primary cells also called Reserve Batteries .

They contain a metallic salt electrolyte which is non-conducting when solid at ambient temperature but which is an excellent ionic conductor when molten.

Activated by a pyrotechnic charge, they provide a high burst of power for a short period. (A few tens of seconds to 20 minutes or more)

They are rugged and safe with an indefinite shelf life in storage which makes them ideal for military applications.

Typical chemistry is Lithium Iron disulphide. The electrolyte is normally a eutectic mixture of lithium and potassium chlorides.

Power output ranges from a few watts to several kilowatts.

Advantages

Able to withstand severe mechanical stresses of acceleration, shock, vibration and spin

Rugged

Reliable

Safe

High power and energy densities

Instantaneous activation

Active chemicals are inert until activated

Long unactivated shelf life - Up to 20 years

No maintenance

Design can be optimised for power or capacity.

Shortcomings

Operating temperature of 400 to 700°C must be maintained by the pyrotechnic charge throughout the duration of the application.

Need insulation to conserve heat once activated.

Applications

Military applications

Missiles

Weapons systems

Costs

Expensive

Biothermal Battery

Low temperature, low power devices using nano scale materials and semiconductor technology to convert thermal energy produced by the human body into electrical energy.

Resulting power can be used to trickle charge batteries for medium power devices or to drive low drain applications such as heart pacemakers.

Long life.

Can be implanted.

Low energy conversion efficiency due to low operating temperature.

Use limited to low power applications.

History

See also Themo-electric Batteries based on the direct conversion of heat into electricity.

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Nickel Iron (NiFe) Batteries

Characteristics

This rechargeable battery was introduced in 1900 by Thomas Edison. It is a very robust battery which is tolerant of abuse and can have very long life even if so treated. It is often used in backup situations where it can be continuously charged and can last for 20 years. Also called Nickel Alkaline of NiFe batteries.

The open circuit voltage of these cells is 1.4 V, and the discharge voltage is about 1.2 V.

Advantages

Very robust.

Withstands overcharge and over-discharge

Accepts high depth of discharge - deep cycling.

Can remain discharged for long periods without damage, whereas a Lead Acid battery needs to be stored in a charged state.

The ability of this system to survive frequent cycling is due to the low solubility of the reactants in the electrolyte - potassium hydroxide (KOH).

Lifetime of 30 years possible

Shortcomings

Low cell voltage.

Very heavy and bulky.

The low reactivity of the active components limits the high rate performance of the cells. They cells take a charge slowly, and give it up slowly.

Low coulombic efficiency, typically less than 65%

Steep voltage drop off with state of charge

Low energy density.

High self discharge rate.

Applications

Traction applications

Fork lift trucks

Costs

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Nickel Cadmium Batteries

Characteristics

1.2 Volt secondary cells using an alkaline chemistry with energy density about double that of lead acid batteries.

Invented in 1899 but only introduced in volume in the early 1960's

They use nickel hydroxide Ni(OH)2 for the positive electrode (cathode), cadmium Cd as the negative electrode (anode) and an alkaline potassium hydroxide KOH electrolyte. (KOH is also one of the main ingredients in drain cleaners and soft soaps)

Their small size and high rate discharge capacity made portable tools and other consumer applications practical for the first time.

The cells are sealed and utilise a recombinant system to prevent electrolyte loss and extend the useful life.

Once the battery of choice for low power portable products they have lost market share to the newer Nickel Metal Hydride batteries.

Advantages

Low internal resistance

High rate charge and discharge rate possible

Up to 10C discharge rates for short periods typical

Flat discharge characteristic (but falls off rapidly at the end of the cycle)

Tolerates deep discharges - can be deep cycled.

Wide temperature range (Up to 70°C)

Typical cycle life is over 500 cycles.

Charging process is strongly endothermic-the battery cools during charging. This makes it possible to charge very quickly, as the I^2R heating and endothermic chemical reaction counteract each other.

Rapid charge typically 2 hours, but can be as low as 10 to 15 minutes.

The coulombic efficiency of nickel cadmium is over 80% for a fast charge but can drop to below 50% for slow charging.

The sealed nickel-cadmium cell can be stored in the charged or discharged state without damage. It can be restored for service by recharging several charge/discharge cycles.

Available in a large variety of sizes and capacities

Shortcomings

A major drawback of this technology is its susceptibility to memory effect.

Originally, the terms memory effect or memory problem was coined to describe a cyclic memory problem where the NiCad battery would "remember" the amount of discharge for previous discharges and limit the recharge life of the battery. The problem is less prevalent with modern Ni-Cd batteries, which are designed to avoid cyclic memory issues.

The memory effect is caused by a change in crystalline formation from the desirable small size to a large size which occurs when a NiCad battery is recharged before it is fully discharged. The growth of large crystals increases the cell impedance and can eventually prevent the battery from discharging beyond that point and/or cause rapid self-discharge of the battery.

The growth of large crystals can be avoided by either completely discharging it each time it is used or by using a NiCad battery charger which has a built-in discharge circuit.

Memory effect can sometimes be reversed by putting the battery through several complete discharge and recharge cycles which helps to recover the smaller crystal formations. This is called reconditioning.

NiCad batteries are also prone to damage by overcharging.

Low cell voltage of 1.2 Volts compared with primary alkaline cells 1.5 Volts and only quarter of the capacity of the alkaline cells.

Self re-sealing safety vents must be incorporated to prevent damage due to overheating and pressure build up.

The use of Cadmium in consumer products is now deprecated on environmental grounds.

Gradually being phased out in favour of Nickel metal hydride and Lithium technologies which have superior energy density characteristics and performance characteristics.

Charging

Run down fully once per month to avoid memory effect.

Do not leave battery in charger.

Slow charging method: Constant current followed by trickle charge.

Rapid charging method uses Negative delta V (NDV) charge termination.

Applications

Motorised equipment

Power tools

Two way radios

Electric razors

Commercial and industrial portable products

Medical instrumentation

Emergency lighting

Toys

Costs

Relatively inexpensive for low power applications but between three and four times more expensive than lead acid for the same capacity.

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Nickel Metal Hydride Batteries

Characteristics

Nickel-metal-hydride batteries are related to sealed nickel-cadmium batteries and only differ from them in that instead of cadmium, hydrogen is used as the active element at a hydrogen-absorbing negative electrode (anode). This electrode is made from a metal hydride usually alloys of Lanthanum and rare earths that serve as a solid source of reduced hydrogen that can be oxidized to form protons. The electrolyte is alkaline potassium hydroxide. Cell voltage is 1.2 Volts

The NiMH battery was patented in 1986 by Stanford Ovshinsky, founder of Ovonics.

The basic concept of the nickel-metal hydride cell negative electrode emanated from research on the storage of hydrogen for use as an alternative energy source in the 1970s. Certain metallic alloys were observed to form hydrides that could capture (and release) Hydrogen in volumes up to nearly a thousand times their own volume. By careful selection of the alloy constituents and proportions, the thermodynamics could be balanced to permit the absorption and release process to proceed at room temperatures and pressures.

Now that the technology is reasonably mature, NiMH batteries have begun to find use in high voltage automotive applications. The energy density is more than double that of Lead acid and 40% higher than that of NiCads

They accept both higher charge and discharge rates and micro-cycles thus enabling applications which were previously not practical.

The components of NiMH batteries include a cathode of Nickel-hydroxide, an anode of Hydrogen absorbing alloys and a Potassium-hydroxide (KOH) electrolyte. Like NiCd batteries, Nickel-metal Hydride batteries are susceptible to a "memory effect" although to a lesser extent. They are more expensive than Lead-acid and NiCd batteries, but they are considered better for the environment.

Losing market share to Lithium batteries.

Advantages

High energy density

Typical cycle life is 500 cycles (less than Nicads).

Can be deep cycled.

Using NiMH batteries, up to 3000 cycles at 100 % Depth of Discharge (DOD) have been demonstrated. At lower depths of discharge, for example at 4 % DOD, more than 350.000 cycles can be expected.

Robust - NiMH batteries also tolerate over charge and over discharge conditions and this simplifies the battery management requirements.

Low internal impedance

Flat discharge characteristic (but falls off rapidly at the end of the cycle)

Wide operating temperature range

Rapid charge possible in 1 hour

Trickle charging can not normally be used with NiMH batteries since overcharging can cause deterioration of the battery. Chargers should therefore incorporate a timer to prevent overcharging.

Because of potential pressure build up due to gassing they usually incorporate a re-sealable vent valve

Reconditioning is possible.

Environmentally friendly (No cadmium mercury or lead)

Shortcomings

Very high self discharge rate, nearly ten times worse than lead acid or Lithium batteries.

Can be stored indefinitely either fully charged or fully discharged.

Suffers from memory effect though not as pronounced as with NiCad batteries

Battery deteriorates during long time storage. This problem can be solved by charging and discharging the battery several times before reuse. This reconditioning also serves to overcome the problems of the "memory" effect.

High rate discharge not as good as NiCads

Less tolerant of overcharging than NiCads

As with NiCads the cells must incorporate safety vents to protect the cell in case of gas generation.

The coulombic efficiency of nickel metal hydride batteries is typically only about 66% and diminishes the faster the charge.

While the battery may have a high capacity it is not necessarily all available since it may only deliver full power down to 50% DOD depending on the application.

Cell voltage is only 1.2 Volts which means that many cells are required to make up high voltage batteries.

Lower capacity and cell voltage than alkaline primary cells.

Charging

Run down fully once per month to avoid memory effect.

Do not leave battery in charger.

Slow charging method: Constant current followed by trickle charge.

Rapid charging method uses dT/dt charge termination.

Use timer cut off to avoid prolonged trickle charge.

Applications

Low cost consumer applications

Electric razors

Toothbrushes

Cameras

Camcorders

Mobile phones

Pagers

Medical instruments and equipment

Automotive batteries

Costs

Originally more expensive than NiCad cells but prices are now more in line as NiMH volumes increase and the use of toxic Cadmium based cells is deprecated.

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Nickel Zinc (NiZn) Batteries

Characteristics

This rechargeable battery like the Nickel Iron battery uses an alkaline electrolyte.

Nickel-Zink batteries were developed as replacements for military Silver-Zinc batteries.

Cell voltage 1.65 Volts

Advantages

High rate capability (25C)

Good cycle life

Fast recharge capability

Can be deep cycled down to 100%.

Uses low cost benign materials.

Shortcomings

Heavy and bulky.

Low energy density.

High self discharge rate.

Solubility of zinc in the alkaline electrolyte limited life cycle.

Formation of zinc dendrites across the electrodes during recharge results in short circuiting and shortened life.

Applications

Traction applications

Electric Bicycles

Scooters

Lawnmowers

Costs

Low cost but higher than Lead acid

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Nickel Hydrogen Batteries (Ni-H_2)

Characteristics

Nickel Hydrogen batteries can be considered as hybrid batteries combining NiCad battery and fuel cell technologies, using pressurised hydrogen in place of the cadmium electrode. They were developed for aerospace applications and are still the number one energy storage system in many satellite projects.

Nickel Hydrogen cells employ the same nickel hydroxide Ni(OH)2 for the positive electrode (cathode) as Nickel Cadmium cells and the same alkaline potassium hydroxide (KOH) for the electrolyte. The negative electrode (anode) however uses Hydrogen in gaseous form as the active material instead of Cadmium. In some ways the anode current collector resembles a fuel cell electrode with a surface of Platinum or Palladium. It does not store Hydrogen and is not transformed but simply acts as a catalytic surface which provides or absorbs electrons. In the discharged state, Hydrogen is absorbed by the Nickel hydroxide.

Since the Hydrogen remains in gaseous form within the cell when the cell is charged, the case has to withstand very high pressures of up to about 7 X 10^6Pascals (70 bar). Because of this, Nickel Hydrogen cells must be hermetically sealed.

History

Advantages

Light weight and high gravimetric energy density.

High cycle life (50,000 cycles) and calendar life (15 years)

Can be deep discharged.

Abuse tolerant.

Maintenance free.

Because Hydrogen is generated during charging and absorbed during discharging, the gas pressure can be used as a simple measure of the State of Charge (SOC)

Shortcomings

Low volumetric energy density due to gaseous Hydrogen

High self discharge rate

Needs high pressure storage and exotic materials

Limited applications due to high cost.

Applications

Aerospace

Costs

Very expensive

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High Temperature Batteries

Since the mid 1960s much development work has been undertaken on batteries using Sodium for the negative electrodes. Sodium is attractive because of its high reduction potential of -2.71 Volts, its low weight, its non toxic nature, its relative abundance and ready availability and its low cost. All these factors offer the prospect of batteries with very high power and energy densities.

Unfortunately in order to construct practical batteries using sodium electrodes, the sodium must be used in liquid form. Since the melting point of sodium is 98 °C this means that sodium based batteries must operate at high temperatures, typically in excess of 270 °C. This in turn brings problems of thermal management and safety and places more stringent requirements on the rest of the battery components.

The first commercial battery produced was the Sodium/Sulphur battery which used liquid sulphur for the positive electrode and a ceramic tube of beta-alumina for the electrolyte. Corrosion of the insulators can be a problem in the harsh chemical environment since they gradually become conductive and the battery self-discharge rate increases.

Later developments included the Zebra Battery which used a solid metal positive electrode of Nickel Chloride. This was intrinsically safer and allowed larger cells to be made.

The special safety precautions and complex thermal management required for these batteries conspire to prevent the achievement of the very high energy densities theoretically possible. With the advent of the newer Lithium technologies enthusiasm for these high temperature batteries is beginning to wane.

High temperature technology is also used in Thermal Batteries . These batteries us an electrolyte which is solid and inactive at normal ambient temperatures. The batteries only become active at high temperatures by the application of heat from an external source to liquefy the electrolyte. These batteries are use almost exclusively for military applications

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Redox Batteries

Characteristics

The Redox battery is an example of both a Flow Battery and a two electrolyte system. In this case, it depends on two different active aqueous electrolytes of vanadium dissolved in sulfuric acid separated by a membrane at which ionic interchange takes place. The chemical reactions take place on inert graphite electrodes stacked in a bipolar configuration. The electrolytes are stored externally from the battery and must be pumped through the cell for the chemical action to take place.

Sloping discharge characteristic with output voltage varying from 1.5 to 1.0 Volts

The name Redox is a contraction of the terms "Reduction" and "Oxidation". Although these particular batteries are named after this chemical reaction, the Redox action is common to most all Galvanic cells.

Advantages

Very high power output (Tens of kiloWatts)

Fast recharge by replacing spent electrolyte

Capable of long life due to replacement of electrolyte.

Can be fully discharged

Use non toxic materials

Shortcomings

Complex.

Low energy density

Little commercial take up to date

Applications

Suitable for high power rechargeable storage systems in applications such as load levelling.

Costs

High costs since little progress from experimental systems to high volume applications.

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Zebra Batteries

Characteristics

High power, high capacity cells suitable for electric traction applications.

High Temperature Battery operating at over 270°C

Sodium Nickel Chloride (NaNiCl) chemistry giving a nominal operation cell voltage of 2.58 Volts

Advantages

High energy density (5 times higher than Lead acid)

Large cells (up to 500Ah) possible

Cycle life better than 1000 cycles

Tolerant of short circuits

Safer than Sodium Sulfur cells

Typical cell failure is short circuit which does not cause complete failure of the battery.

Low cost materials

Shortcomings

Suitable for large capacity batteries only (> 20KWh)

Limited range of available sizes and capacities. (Large multi-cell blocks)

Only one factory in the world produces these batteries.

High internal resistance

Molten sodium electrode

High operating temperature.

Preheating needed to get battery up to the 270°C operating temperature. (Up to 24 hours from cold)

Uses 14% of its own capacity per day to maintain temperature when not in use.

Thermal management needed

Applications

Traction applications, EVs, HEV, and Railway

Costs

Expensive

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Other Galvanic Cell Chemistries

Solid State Cells

These are cells using solid electrolytes. They offer the advantages of no leakage or gassing, long shelf life, excellent packaging efficiency, no separators and miniature designs. they depend on electrolyte materials with high ionic conductivity and negligible electronic mobility. The former provides low internal resistance while the latter prevents self discharge providing long life. The Lithium Iodine primary cell used in heart pacemakers is an example of such a cell.

History

Nanotechnology

Nanomaterials (nanocrystalline materials) are currently being used for electrodes and separator plates in experimental NiMH and Lithium ion batteries where their foam-like microstructure provides a very large porous active surface area which can hold and deliver considerably more energy than their conventional counterparts. C rates of 10 to 100 times higher have been claimed. (This implies charging the battery in one minute!)

These cells are not yet commercially available.

Mercury Cells

The original technology for primary button cells was the mercury cell, which had a mercuric oxide cathode, an anode made of an amalgam of mercury and zinc, and an electrolyte consisting of potassium hydroxide mixed with zinc hydroxide. It is essentially an alkaline cell with a different and more efficient cathode. It provided an open circuit voltage of 1.35 Volts. Designed as a replacement for the carbon-zinc cell, this battery could not only resist high temperatures and high humidity, but also had better discharge characteristics, longer shelf life, and greater efficiency.

As mercury is toxic, mercury cells are now banned in the US and some other countries and they are now only a curiosity.

Silver-Oxide or Zinc-Air cells make good or superior alternatives.

History

Metal Air Cells

A very practical way to obtain high energy density in a galvanic cell is to utilize the oxygen in air as a "liquid" cathode. A metal, such as zinc or aluminium, is used as the anode. (See below) The oxygen cathode is reduced in a portion of the cell that is physically isolated from the anode. By using a gaseous cathode, more room is available for the anode and electrolyte, so the cell size can be very small while providing good energy output.

Rechargeable Aluminium-Air Cells

They have long shelf-life and high energy density but are complex and have low efficiency.

Aluminium-air batteries obtain their energy from the interaction of aluminium with air. The incoming air must be filtered, scrubbed of CO_2, and dehumidified; the water and electrolyte must be pumped and maintained within a narrow temperature range - hence the complexity of the battery.

The batteries are not electrically recharged but are "refueled" by replacing the aluminium anodes and the water supply.

Special versions which use seawater electrolytes have also been developed.

A new generation of Aluminium-Air cells recently patented in Finland using nanotechnology have overcome the problems associated with recharging aluminium cells and promise very high energy and power densities.

Still under evaluation and not yet available in production quantities.

History

See also Zinc Air Cells and Lithium Air Cells

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Reserve Batteries

Also called deferred-action batteries, reserve batteries are special purpose primary batteries usually designed for emergency use. The electrolyte is usually stored separately from the the electrodes which remain in a dry inactive state. The battery is only activated when it is actually needed by introducing the electrolyte into the active cell area. This has the double benefit of avoiding deterioration of the active materials during storage and at the same time it eliminates the loss of capacity due to self discharge until the battery is called into use. They can thus be stored for 10 years or more yet provide full power in an instant when it is required.

Examples are Ampoule batteries Thermal Batteries and Water-activated batteries

Ampoule batteries store the electrolyte in a separate ampoule which is incorporated into the battery case. When the battery is needed, the ampoule is broken open allowing the electrolyte to enter the cell. This technique has been used for military fuses as well as marine applications.

The electrolyte in **Thermal batteries** is solid and inactive at normal ambient temperatures. It only becomes active in molten form at high temperatures by the application of heat from an external source. These batteries are use almost exclusively for military applications.

In **Water-activated batteries** the electrolyte is usually water or seawater as the name implies.
An added advantage is that the water does not have to be transported around with the cell since
it can be obtained local when it is required. These batteries have many marine and military applications and find extensive use with the emergency services.

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Fuel Cells

Characteristics

Fuel cells have been around longer than most batteries - the principle of the fuel cell was discovered in 1839 by Sir William Grove. They generate electricity from the reaction of hydrogen with oxygen to form water in a process which is the reverse of electrolysis.

The fuel cell relies on a basic oxidation/reduction reaction, as with a battery, but the reaction takes place on the fuel rather than the electrodes. The fuel cell produces electricity as long as the cell receives a supply of fuel and can dispose of the oxidized old fuel . In a fuel cell, the anode usually is bathed in the fuel; the cathode collects and makes available the oxidant (often atmospheric oxygen). An ion-conducting membrane separates the two, allowing the reaction to take place without affecting the electrodes.

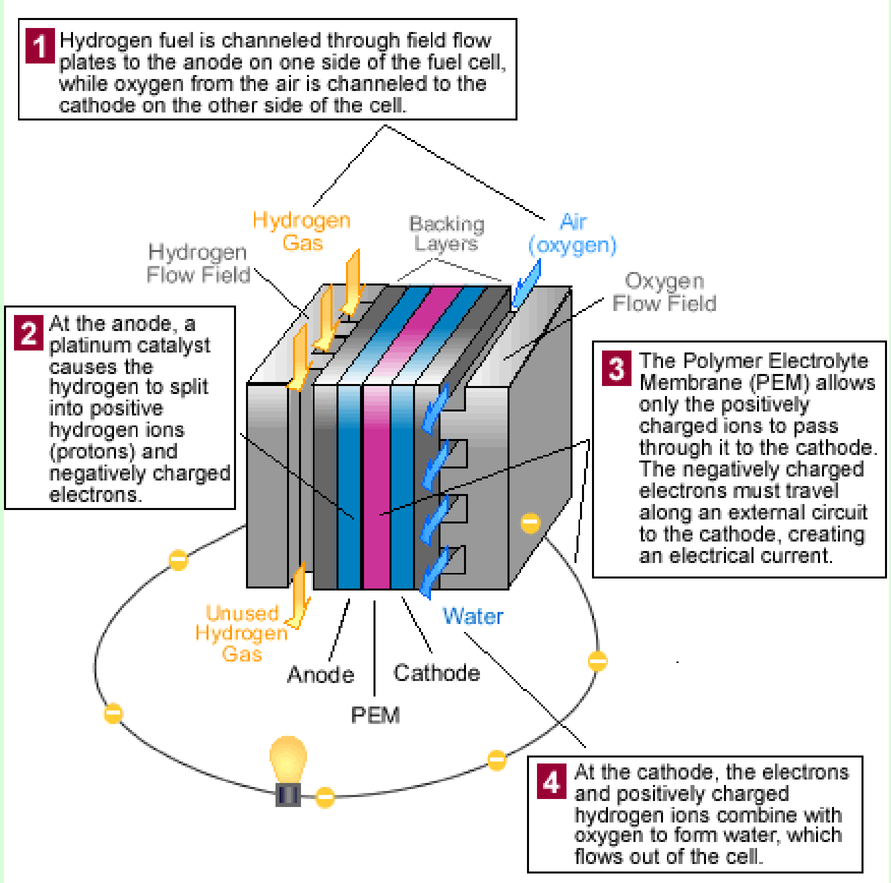
There are six major fuel cell technologies are currently being pursued for different applications each with its own characteristics. Some operate at high temperatures, some use exotic electrode materials or catalysts, all are very complex.

- Alkali
- Phosphoric Acid
- Solid Oxide
- Molten Carbonate
- Proton Exchange Membrane PEM
- Direct Methanol DMFC

They have been proposed for a wide range of applications from powering laptop computers, through automotive traction to high power load levelling.

The most active developments are currently in the automotive sector where the favoured technology is PEM. This promises a high conversion efficiency of over 60% and an energy density of 120 W/Kg. DMFC do not use Hydrogen fuel with its associated supply problems, but the more convenient liquid Methanol. They are less efficient but offer compact and convenient designs suitable for future consumer electronics applications.

How a Fuel Cell Works



Source: U.S. Department of Energy

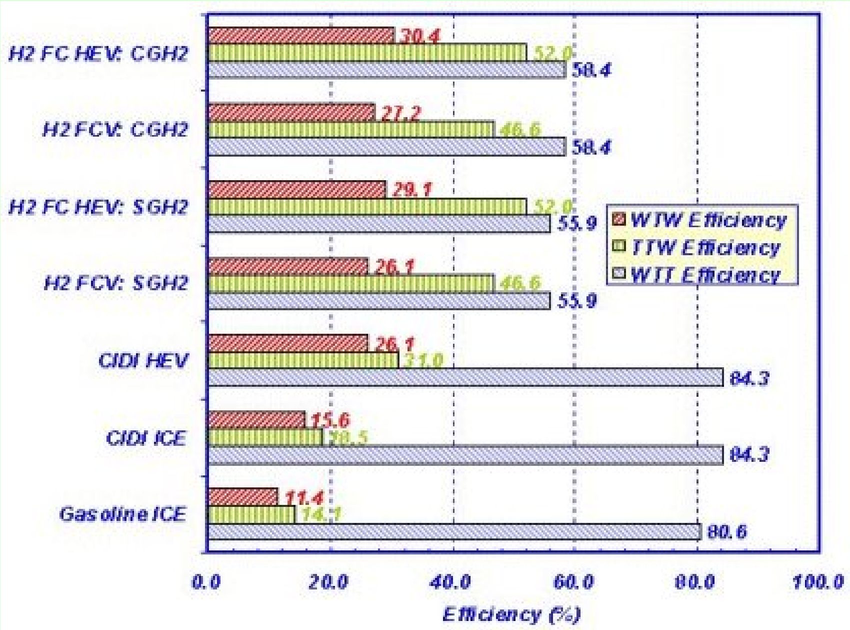
The potential power generated by a fuel cell stack depends on the number and size of the individual fuel cells that comprise the stack and the surface area of the PEM.

Advantages

- Fuel cell power is usually proposed as the green, alternative to the internal combustion engine, fuelled only hydrogen and leaving no pollutants other than water.
- Simple fuel requirements needing hydrogen fuel only, taking their oxygen from the air.
- No recharging is necessary.
- No time lost through recharging. (Acts like a perpetual primary cell)
- So long as fuel provided, the cells can provide constant power in remote locations.
- Practical fuel cells already have efficiencies as high as 60%
- Fuel cells deliver maximum efficiency at low power levels.(This is the reverse of the internal combustion engine)

- For transport applications fuel cell vehicles offer higher "well to wheel" (WTW) efficiencies than conventional internal combustion engines.

Well to Wheel Efficiencies



Source: US Department of Energy

CGH2 - Centrally Generated Hydrogen

SGH2 - Station Generated Hydrogen

CIDI - Compression-Ignition Direct-Injection

The graphs show that, compared with an internal combustion engine, the higher "tank to wheel" (TTW) efficiency of the fuel cell power unit more than compensates for the low "well to tank" (WTT) distribution efficiency resulting from the need to compress the hydrogen or to generate it on board.

The fuel cell vehicle however does not offer significant efficiency improvements over the hybrid diesel.

See more on Costs below.

Shortcomings

The environmentally friendly credentials of fuel cells overlook the processes needed to generate and distribute the hydrogen fuel. Fuel cells merely shift the pollution from the vehicle to some other location.

Today, 98% of hydrogen is produced from fossil fuel sources.
According to researchers Andrew and Jim Oswald from Warwick University: To replace petrol and diesel used for road transport in Britain with hydrogen produced by the electrolysis of water would require the building of 100 nuclear power stations or 100,000 wind turbines. If the wind turbines were sited off-shore, this would mean an approximately 10-kilometre-deep strip of wind turbines encircling the entire coastline of the British Isles. If sited on-shore then an area larger than the whole of Wales would have to be given over to wind turbines.

A major factor inhibiting market take off is the lack of available infrastructure to provide the hydrogen fuel. Hydrogen fuel can be supplied in pure form in cylinders or the on board cylinders can be refilled at special refueling stations. Despite safety precautions there is still a perception by the general public that hydrogen fuel is unsafe.

Alternatively hydrogen can be generated on board, as required, from hydrocarbon fuels such as Ethanol, Methanol, Petrol or Compressed Natural Gas in a process known as reforming. This is not an ideal solution. Reforming generates carbon dioxide as a waste product losing some of the green benefits of fuel cells. It is also expensive and it is like carrying your own chemical plant with you, but it does simplify the fuel supply infrastructure problem, however the fuel could just as easily power an internal combustion engine directly.

Even ignoring these problems there are still many shortcomings in using fuel cells for prime motive power.

The low cell voltage 0.6 - 0.7 Volts means that the system needs a lot of cells to obtain a normal operating voltage of 200 - 300 Volts to power the drive train motor.

Power is generated as required but the process is not reversible within the fuel cell and so, like a primary cell, it can not accept regenerative braking loads. Fuel cells generate electrical energy but they can not store electrical energy.

Fuel cells have a low dynamic range and slow transient response which causes an unacceptable lag in responding to calls for power by the driver. A power boost from a battery or from supercapacitors is therefore needed to achieve the desired system performance.

Most designs need to work at high temperatures in order to achieve reasonable operating efficiencies. To generate the same efficiencies at lower temperatures requires large quantities of expensive catalysts such as platinum.

Low temperature freeze-up of the electrolyte.

Electrodes which are prone to contamination.

Due to the need to use of exotic materials and complex system designs the system are still very expensive.

Theoretically a fuel cell should be all that is needed to power an electric vehicle, however batteries are still needed to support fuel cell systems.

Battery Support

Batteries are needed in fuel cell vehicle applications for the following functions:

- During start- up to heat the fuel cell stack and the electrolyte to the optimum working temperature
- To pump the working fluids through the stack (air, hydrogen, water)
- To power the reformer if hydrogen is generated on board
- To provide short term power boosts to compensate for the fuel cell's slow response to sudden power demands (acceleration)
- To capture regenerative braking energy
- To power the vehicle's low voltage electrical systems

Applications

For automotive applications fuel cells are only suited to hybrid applications for providing the base power load with the demand peaks and troughs, and regenerative braking, being accommodated by batteries or booster capacitors. The fuel cell can therefore be dimensioned to work at its optimum working point, providing the average power rather than the peak power requirement permitting significant cost savings.

Fuel cells have been used successfully in aerospace applications.

Simple low power demonstrator kits are available for education purposes.

Perhaps the best applications for fuel cells will be for high power load levelling.

Prototypes of Direct Methanol cells are currently being trialled for mobile phone and laptop computer applications.

Costs

For a true comparison of alternative system efficiencies, costs and benefits, each alternative should be based on the same fuel source. Using oil as the original source of the energy the "well to wheel" cost provides a rational comparison of the energy utilisation efficiency of different systems.

But oil is not the only source of energy. Electrical energy used to power electrical vehicles or to produce the hydrogen to feed the fuel cells can be derived from a wide variety of sources. These may include power stations fuelled by oil, or coal or hydro or nuclear power, or renewable resources such as wind, wave and solar power. There can thus be a huge variation in costs and environmental impacts depending on the methods used to supply the necessary fuel.

Although many working systems for different applications have been built, practical, cost effective products are still perhaps ten years away.

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Solar Cells

Photovoltaic (PV) cells - photocells

Characteristics

Solar cells do not utilise chemical reactions to produce electric power. They convert sunlight energy into electric current. They do not store energy.

The cell voltage is proportional to the amount of sunlight falling on the cell but is generally less than 0.5 Volts.

The sun's energy reaching the surface of the earth is roughly 1 kilowatt per square metre.

Solar cell conversion efficiencies have improved in recent years to between 20% and 30% but they still only generate 150 W/m^2 in bright sunlight. A reasonable maximum size of a solar array in a typical car would be 3 m^2. In the best case, in bright sunlight, this would generate only 0.5 kW (less than 1 bhp) of power which is not enough to drive a road vehicle or even to charge a reasonable sized battery.

Taking into account the hours when there is no sun, or hazy conditions and that the solar cell would often be shielded or tilted at an angle to the sun, the average power generated by the array would be less than 30 W/m^2 even in a sunny climate. This makes solar power impractical for driving any other than specialist low power demonstration vehicles.

Cells convert sunlight energy into electric current they do not store energy. Sunlight is the “fuel”

Typical commercially available PV panels have an efficiency of about 15%, which means that they can deliver about 150 watts of power per square metre.

Polycrystalline cells have the highest efficiency (10-30%), and very long lifetimes because the crystal structure is very stable, but they are very expensive.

Thin film or amorphous silicon cells are the type most commonly found in calculators. Each cell is made from non-crystalline thin films of silicon atoms, and typically have a uniform gray appearance. These cells are cheaper but they tend to have lower efficiencies (5-10%) and shorter lifetimes.

A domestic solar power system includes the following components

- **PV panels**

- **Batteries:** Typically about 12 deep-cycle lead acid batteries
- **Charge controller:** To regulate the charging of the batteries
- **Inverter to** convert the low voltage DC power from the batteries into AC mains power for use by appliances

Advantages

Inexhaustible energy source

PV manufacturers guarantee their products for up to 20 years.

Shortcomings

Depends on sun

Typically, the output of any industrial PV module is reduced to 5-20% of its full sun output when it operates under cloudy conditions.

Low cell voltage <0.5 Volts.

Very low conversion efficiency

PV systems convert light directly into electricity using semiconductor technology @ around 30% efficiency

Thermal systems (hot water, pool heaters) produce heat from the sun’s radiation @ +40 % efficiency

Large surface area of cells exposed to the sun needed for high power systems.

High capital cost for high power systems.

Deep discharge batteries are required to store and level the power generated from PV systems.

Applications

Suitable for low power applications such as calculators, portable lamps, watches and battery chargers.

Remote telemetry and communications.

Advertising signs

Satellites, the first application to use solar power.

A typical house in the USA sunbelt can be powered with about 200 square feet of solar panels.

Still not cost effective for high power applications.

Costs

In the sunny parts of the USA, the cost of larger PV systems (greater than 1 kW) is measured in "levelised" costs per kWh--the costs are spread out over the system lifetime and divided by kWh output. The levelised cost is now about $0.25 to $0.50/kWh. At this price, PV is cost effective for residential customers located farther than a quarter of a mile from the nearest utility line.

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See also Grätzel Cells

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Battery Quotation Request

You can use this form to find out how we can help you to find a custom battery pack for your project.

Please note that Woodbank Communications does not sell batteries. We will however pass on your request to a potential supplier. These facilities are only available to bona fide business partners and are only intended for high volume purchases of custom batteries, not for standard off-the-shelf products or low volume specials.

Please check the FAQ number 2 before you fill in the form.

There's no need to fill in all the boxes, but please try to give us as much information as possible so that we get you a more accurate answer.

Go to "**How to Specify Batteries**" and " **Battery Management Systems"** if you need help with the questions.

Application	Application	
Preferred cell chemistry (If known)	No preference	
Quantity Required		
Prototypes		Units
Annual Requirement		Units
Voltage		
Nominal		Volts
Minimum		Volts
Maximum		Volts
Discharge Current		
Discharge characteristic	Constant	
Average		mA
Peak		mA
Minimum		mA
Capacity		mAh
Charging current	Tick any which apply	

Trickle charge ☐
Float charge ☐ Charging during use
Off line ☐
Never ☐ (Primary cells)

Charging characteristic Random
Charging rate/time mA
Time between charges Hours

Do you require a charger to be supplied ○ Yes ● No

If you require a quotation for a charger you will be invited to supply supplementary information on the acknowledgement page after you submit this form

Are parallel cell strings allowed ○ Yes ○ No ● Don't know ○ Don't care

Life expectancy Cycles

Environmental Conditions

Ambient temperature °C
Maximum temperature °C
Minimum temperature °C

EMC restrictions Tick any which apply

Don't know ☐
Emissions ☐
Susceptibility ☐

Dimensions

Length mm
Width mm
Height mm

Weight grams
Volume Litres

Termination/Connector Type Custom

Packaging None

Pack Repairability Pack not repairabl

Built in electronics (BMS) Tick any which apply

None
Battery Management System ☐
Authentication ☐
Pre-charge circuits ☐
Fuel gauge (SOC) ☐
State of health indication (SOH) ☐
Thermal protection ☐
Over current/voltage protection ☐
Progressive control required ☐
Cell equalization ☐
CAN Bus ☐
Communications/control bus ☐
Software limit setting ☐
Data logging (Log Book) ☐
Indicator lights ☐
Battery current and voltage display ☐
Individual cell condition display ☐
Limp home mode ☐
Enhancements - Remote monitoring ☐
Enhancements - GPS ☐
Other - Please specify below

Safety Approvals Required Tick any which apply

UL ☐
CE ☐
FCC ☐
TUV ☐
CSA ☐
NF ☐

ISO9000 ☐
QS9000 ☐
DEF ☐
MIL ☐
Other ☐
Don't know ☐

Project Start Date Immediately 2009

Target Price Per Unit

Battery ☐ £ ☐

Charger ☐ £ ☐

System ☐ £ ☐

Any questions or special requirements ?

☐

Your questions will be answered by a real person, not a computer, so please allow time to process these responses during normal UK office hours.

Please tell us how to contact you.

Name * ☐

Company * ☐

Telephone * ☐

E-mail * ☐

* Required Fields

Note: Unless you give us your contact details we will not be able to contact you with the answers.

[Submit Form] [Clear Form]

Go to the "**Charger Quotation**" page if you want to specify an appropriate charger

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Woodbank Communications Ltd, South Crescent Road, Chester, CH4 7AU, (United Kingdom)

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"AC Batteries"

Characteristics

Some specialist battery packs have built in electronics such as inverters which generate the AC power from the battery's DC output voltage to provide portable mains power remote from the utility supply grid or emergency mains back up power.

Battery characteristics / requirements

- Short term power supply

  Many emergency power systems are only required to provide power long enough to enable a graceful shut down of an application to prevent loss of data or loss of continued control of a critical industrial process or medical procedure.

  Where a vital process must be maintained it may only be necessary for the battery to power the critical application until an alternative energy supply (standby generator) can be brought on line. For such critical applications a dedicated Uninterruptible Power Supply (UPS) may be provided. This usually contains a battery with sufficient capacity to power only the critical application for the expected duration of any outage and a built in inverter to provide the AC power to the load. The rest of the establishment will have to live with the power outage.

  These applications require deep discharge batteries but they are rarely called into use and are not subject to repetitive duty cycles.

- Long term power supply

  Deep discharge batteries are also required for load levelling applications to provide power on demand from intermittent supplies such as solar, wind and wave power applications. These applications require robust, long life batteries able to tolerate constant charge-discharge cycling.

  For very high power applications such as emergency back ups for the national electrical power grid system or temporary storage of surplus low cost energy, very large capacity batteries are required. While enormous lead acid batteries with capacities up to 40 Megawatt hours or more have been constructed, several unusual systems for storing such large energies have also been implemented. See Alternative Energy Storage Methods.

  In these high power applications the inverter will be a separate unit or the system may generate AC power directly as is the case with pumped storage systems.

Inverter characteristics / requirements

No loss of power to the load

High quality clean sinewave output.

Frequency stabilisation

High efficiency / low loss

Possible integration with battery float or trickle charger

Advantages

Fast acting - Much quicker than rotary or other standby AC generators.

Shortcomings

Limited capacity compared with motor driven rotary generators.

Applications

Uninterruptible power supplies. See UPS

Emergency power

Standby power sources

Load levelling

Costs

Very wide range of costs

See also How to Specify Batteries - Timing Issues and Depth of Discharge

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