Portable Power -- A Designer's Guide to Battery Management

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Summary:

While demands for portability have created great interest in battery technology, this is a field with many choices, few absolutes, continuously improving performance characteristics, and the constant lure of future developments. Since the designer of portable electronic systems is vitally dependent upon his power source, while also sharing a major responsibility for its performance, a good understanding of battery technology becomes mandatory. This paper attempts to aid in this effort by characterizing and comparing a range of battery technologies and providing insight into their selection and application. Since charging techniques are critical to battery performance, practical examples of charging algorithms and associated hardware implementations for the various battery chemistries are also discussed and a versatile battery system evaluator is described.

Introduction

Once upon a time, portability meant that your box had handles on the side; but today it means freedom from the confines of a power cord. This, of course, usually means battery power and thus introduces a whole new technology to the expertise required of system and circuit designers. Not only must these engineers now understand the capabilities and characteristics of the various battery chemistries in order to select the appropriate battery type, but they also share a large portion of the responsibility for battery performance by the way they manage this power.

And management is an important concept. It includes defining both the way the energy is removed from the battery and the way it is replaced. Optimum energy removal can include, for example, lowering the system supply voltage and switching off sections of the circuitry which are temporarily unused, as well as the obvious efforts to apply only low current-drain components. Optimum energy replacement means defining a charging algorithm and method of implementation which will favorably impact the amount of energy put back into the battery, the efficiency and speed at which it is accomplished, and the number of times it may be done. Clearly, each of these issues — along with many others — require decisions which impact all aspects of a system's design. Which is why this subject is titled "Battery Management".

Within this material, we will attempt to describe and compare the various battery technologies which are either available or appear as promising alternatives. While this information should aid in both battery selection and application, as an initial disclaimer it should be recognized that with all the industry resources which are currently being applied to these issues, the best solutions of today may be obsolete by tomorrow. While it is hoped that this information will be useful, it will certainly not replace careful research made for each specific application at the time of need.

Battery Basics

As a first definition, batteries are categorized into two classifications: primary batteries which are intended for a single use and secondary types which can be recharged. This paper will not discuss primary batteries other than to say that they will continue to be a viable choice for applications which value low initial cost and high energy in a small size. While consumers may not like replacing batteries (Definition of a flashlight—a convenient place to store dead batteries.) there are many applications where they have obviously been accepted. As a point of reference, it should be remembered that today's technology for primary cells yields higher performance at lower cost than any form of equivalent rechargeable solution.

In our discussion of rechargeable batteries, there are a few "Basic Truths" which are worthy of recognition:

1. Regardless of chemistry and quality, all batteries will eventually die.
2. Batteries with subtle design and manufacturing differences can yield significant differences in performance.
3. Every manufacturer occasionally makes a battery with less than optimum performance.
4. If test conditions do not exactly duplicate intended use conditions, erroneous performance characteristics will be observed.
5. It is probable that at any given time, new innovations will supplant current "best available technology".

Within this framework, there is still a need for quantitative characterization and, thus, there are a few terms which need be defined and understood to describe battery performance. These definitions are given on the next page.

Battery Chemistries

Fundamentally, a battery operates by the chemical reaction process of oxidation and reduction. Oxidation is the process of releasing electrons while reduction consumes electrons. A battery consists of four elements: an anode made from a material which can contribute electrons, a cathode which will accept the electrons, an electrolyte and a separator. These elements are shown schematically in Figure 1 as they function in both the discharge and charge modes. During discharge, as the anode contributes electrons by oxidation, it also generates positive ions. Similarly, the cathode generates negative ions in the process of accepting electrons. A key element of the battery is the separator which is between the anode and the cathode and, while allowing free flow of the ions, will block the passage of electrons forcing them to flow through

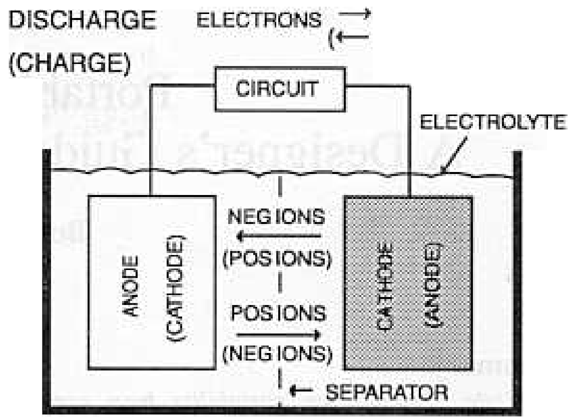

Fig 1. - Elements of a Rechargable Cell

the external circuit to complete the circuit. Note that in a rechargeable cell, the process is reversible so that in discharge, the positive terminal is the cathode and the negative terminal is the anode; while during charging, the positive terminal becomes the anode and the negative terminal is now the cathode.

Typically, the anode is made from a base metal while the cathode is formed from a metallic oxide but that's not a very restrictive definition. There are literally hundreds of combinations of elements and compounds which, in the presence of some type of electrolyte, will produce an electric current. (Are there any here who remember making a battery with two different coins and a piece of paper towel soaked in salt water?) We will, of course, limit this discussion to those combinations which have demonstrated some form of practicality at the time this is written. Within this context, the following seven different battery technologies will be described with comparative data which should help in the selection process:

- **Rechargeable Alkaline**
- **Silver Zinc**
- **Sealed Lead Acid**
- **Nickel Cadmium**
- **Nickel Metal Hydride**
- **Lithium Ion**
- **Zinc Air**

BATTERY DEFINITIONS

A **CELL** is an electro-chemical device capable of supplying, to an external electric circuit, the energy that results from an internal chemical reaction.

While a **BATTERY** can be a single cell, it also refers to a combination of cells connected together in series or parallel to obtain a required voltage or current capability.

A **BATTERY PACK** is an assembly of multiple cells, often including additional cell-monitoring and/or protection components. Many battery packs are manufactured by companies which do not make the cells they contain.

The **CAPACITY** of a battery is its most important figure of merit. It is defined as the amount of current which a battery can steadily deliver which will cause its end-of-life voltage to be reached in one hour, and is measured in units of Amp-hours. While this definition gives us a point of reference, it is far from a constant for a given battery. Two Amps for one hour does not necessarily mean two hours with a one Amp load. Battery capacity will also vary with prior rates of discharge, definition of end-of-life voltage, age, number of cycles, ambient temperature, phase of the moon, etc., etc.

The **"C" RATE** is a measure of a battery's charge or discharge current in terms of its one-hour capacity. For example, a standard AA battery has a one-hour capacity of approximately 500 mAhr. Consequently, a 2C charge rate is 1 A, and a C/10 rate is 50 mA. Note that batteries are usually specified at current levels which are optimum for that battery type.

The **DISCHARGE CURVE** of a battery can be characterized with values for the peak, nominal, and end-of-life voltages. The differences between these values represents the degree of regulation of the battery's voltage or, alternatively, the voltage variation that the system must tolerate.

ENERGY DENSITY can be defined in terms of both volume and weight. The units used herein are Watt-hours / liter and Watt-hours / kilogram and, as one would expect, both are quite important for portable equipment.

SELF DISCHARGE is internal leakage current which results in a loss of charge to an unloaded battery. While it varies considerably with different battery chemistries, it always gets worse with increasing temperatures.

A **TRICKLE CHARGE** is a charge rate which can be delivered to a cell indefinitely without causing damage. This means that the heat it generates can be safely dissipated within the battery. This rate can be used for a simple but slow method of recharge, or it can merely replace any self-discharge which may take place in a fully charged battery.

CHARGE ACCEPTANCE defines the ability of the battery to convert the electrical energy provided by the charger into chemical energy resulting in increased battery capacity. Mathamaticly, it is the ratio of energy stored to energy applied, with the difference in these two terms being dissipated as heat within the battery. Charge acceptance is not constant during charge but diminishes toward zero as the battery approaches full charge.

The **SERVICE LIFE** is the number of times a rechargeable cell may be usefully charged and discharged. While this number should be important, it needs to be used with care as its value is influenced by many defining factors such as the depth and rate of each discharge, the method of recharge, and the definition of how much capacity is available in the "last" cycle.

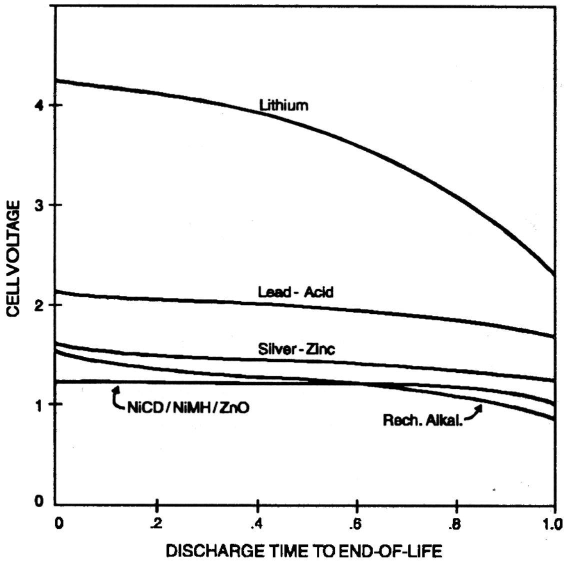

Fig 2. - Normalized Cell Discharge Voltages

The chart shown in Figure 2 compares the discharge voltage characteristics of all these technologies with the horizontal axis normalized to a constant end-of-life.

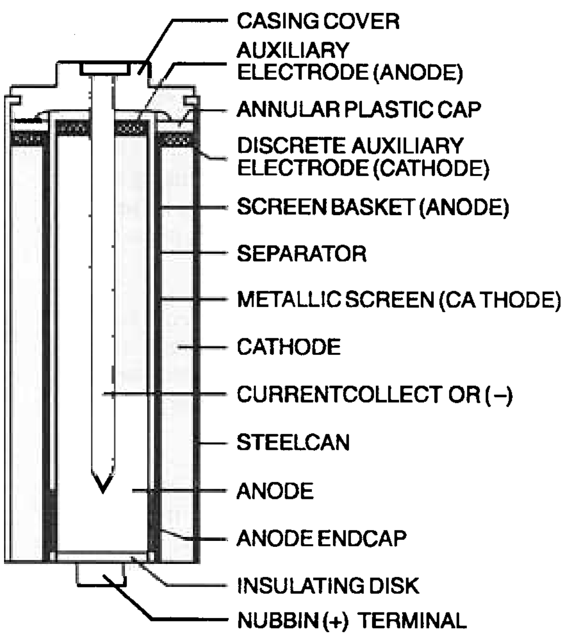

Fig 3. - Rechargable Alkaline Cell

RECHARGEABLE ALKALINE – The Alkaline Manganese Dioxide-Zinc cell has long been well established as a primary, non-rechargeable technology. Although it is best for lower discharge currents, its high energy density and low cost have established its place in consumer products. As the battery discharges, the Manganese Dioxide converts to Manganese Trioxide and when this is complete, the process cannot be reversed. The principle which allows recharging is to prevent complete conversion. While this has been known for many years, it is only recently that Rayovac has perfected the design to the point where a commercial product was viable. A cross-section of their design is shown in Figure 3.

Construction is considerably more complex with the addition of two auxiliary electrodes, two screens, and a new anode endcap. With these extra components plus some proprietary chemistry, the problems of halting the reaction before the battery reaches 40% capacity, plus fixes for some other problems such as swelling of the cathode during charge, is claimed. The result is a battery which is much more expensive than the throw-away types, has approximately half the capacity initially with even further reductions with each recharge cycle, and which also requires that the consumer purchase a $30 charger – a price which would pay for quite a few disposables. It remains to be seen how successful this system will be.

SILVER ZINC – The AgZn battery (actually Silver Oxide-Zinc) is a very mature process, long respected for its stability and reliability. Even today, it is still claimed to have the highest power and energy density (both in terms of volume and weight) of all production-worthy chemistries. As such, its main market has been the defense and space industry where performance was valued over cost. One interesting aspect of this higher cost is that while the AgZn cell contains hazardous materials, expended batteries never end up in landfills but are returned to the manufacturer for silver reclamation.

The nominal voltage of the AgZn cell is 1.5 Volts, the same as an Alkaline unit but the regulation is much better. End-of-life is defined as 1.25V vs. 0.75V for a primary Alkaline and 0.9V for a rechargeable. Charging of a AgZn battery is normally performed with a constant 2.0V source and, with a very low self discharge, neither a float voltage nor trickle charge current is recommended.

AgZn cells use a liquid electrolyte of Potassium Hydroxide so there can be some concern for leakage and venting, however there is little gas generated, or temperature rise, even during high-rate discharge. Manufacturers claim this system has proven to be very safe and highly forgiving of improper handling and accidents. In searching for new markets, the medical electronics industry is being targeted as an area of growth for the same reasons that have made this technology important to the aerospace industry. For most other commercial applications, however, cost represents a severe handicap.

LEAD ACID – While lead-acid batteries have four times the weight of an equivalent silver-zinc system, their low cost and similarly mature technology has led to wide-spread usage. Major advantages of the lead-acid system, in addition to cost, are good service life, high-rate discharge capability, and high reliability.

The construction of a lead-acid cell uses a positive plate of Lead Dioxide, a negative plate of Spongy Lead, and an electrolyte of Sulfuric Acid. Discharging the battery results in both plates converting to Lead Sulfate and the generation of water. While recharging will reverse the process, overcharging begins to produce Hydrogen and Oxygen gas and a subsequent loss of water.

The advent of the sealed lead-acid battery has, with reasonable care in charging, provided significant enhancements to both reliability and ease of use. By using very pure lead in the plates and a special separator which recombines the oxygen created during overcharge, the cell does not dry out and lifetimes of 8-10 years are claimed. As such, these batteries are certainly the optimum choice today for UPS and other backup power systems.

Charging a lead acid battery can be done in a variety of ways but it is important to closely monitor the voltage to prevent extended overcharge. The best chargers are multi-state machines which will initially provide a high current to replace some 80%

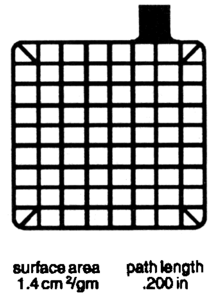

Fig. 4a Typical SLI Flooded Cell

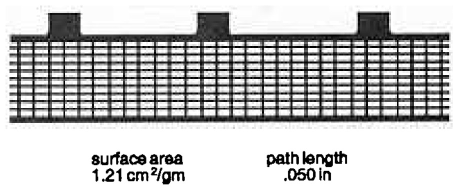

Fig. 4b - Sealed Wound Cell

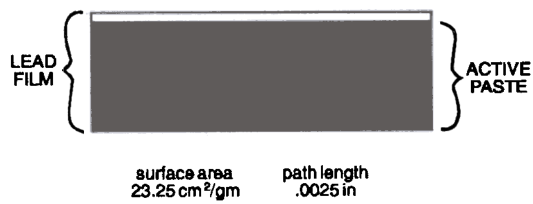

Fig. 4c - Bolder TMF Cell

of the energy as quickly as possible. When a definable over-voltage is reached, the charger will hold that voltage for either a programmable time or until the rising battery voltage causes the current to diminish to a low threshold. At that point, the voltage drops to the float voltage level which can be applied to the fully charged battery indefinitely.

A relatively recent introduction in lead acid battery technology has been announced by Bolder Technologies Corporation. They claim to have successfully replaced the lead grid plates in a conventional design with a thin (.002") lead film coated with an active lead or lead dioxide paste. A promotional comparison is shown in Figure 4 illustrating the reduction in both lead content and mean length for electron flow.

Two of these "thinwall" plates are then spiral wound together with a separator and electrolyte between them as shown in Figure 5. This construc-

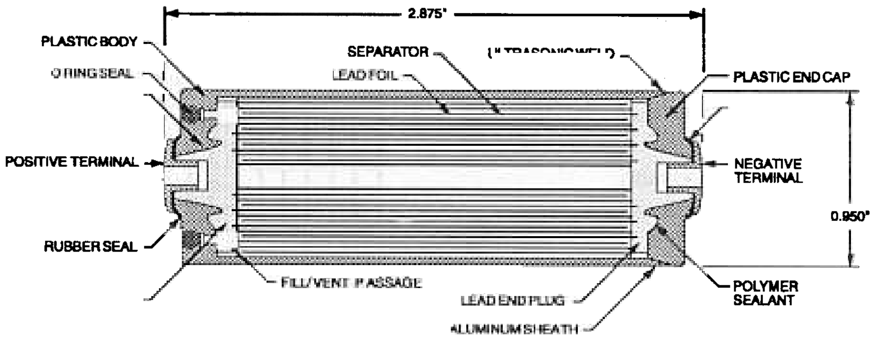

Fig 5. - Bolder 1.5Ahr Thin Film Cell

tion technology offers significant weight reduction along with extremely low internal impedance caused by the very short spacings between plates.

Bolder Technologies has claimed peak power levels in excess of 5000 W/kg and 16,000 W/l. If performance in high volume production confirms these claims, this battery would become very competitive with NiCd and NiMH systems, and broaden the lead-acid market to include light-weight portable equipment.

NICKEL CADMIUM – With sealed cells and half the weight of conventional lead-acid, NiCd batteries have long been the choice for hand-held portable systems. Additional features are a very flat discharge curve and perhaps the highest peak current capability. The NiCd cell is composed of a metallic cadmium anode, a nickel oxide cathode, and a potassium hydroxide electrolyte. Cadmium, being one of those nasty heavy metals is causing significant environmental concern and the added costs and organization of a collection and recycling system may result in a major detriment to future applications. Already several states have passed laws requiring such a system.

The cycle life of NiCd batteries can be over 1000 cycles but these batteries do deteriorate over time more than lead-acid. A major failure mode is reduced recharge capacity caused by a characteristic which has been called "memory effect". This occurs when a cell is partially discharged and then overcharged for an extended period after which the recharge capacity may be limited to the energy removed during the partial discharge. This problem is made worse with long-duration, low rate recharging and while more sophisticated charging systems can minimize memory effect, the charging equipment is significantly more expensive.

While charging NiCd batteries can be as simple as providing a constant current, typically less than C/10, this is often undesirable, both because of the memory effect and the 12 to 16 hours it would take for complete recovery. Higher charge rates must be used with care, however, as significant damage – including destruction – can result with overcharge. The challenge with all high-rate chargers is to know when to stop but the NiCd cell does not show the rapid rise in voltage at end-of-charge as seen in lead-acid types. The only information which is available is shown in the charge characteristics of Figure 6.

The charging of a NiCd battery is an endothermic reaction, that is it accepts heat from its surroundings and thus causes a slight cooling of the battery. Initially, the applied current is working to charge the active electrode materials but as the process nears completion, and the uncharged material diminishes, the impedance of the cell begins to rise and it becomes easier to break down the electrolyte than continue charging. At this point, the process converts to an exothermic reaction, generating both heat and oxygen. While the increased

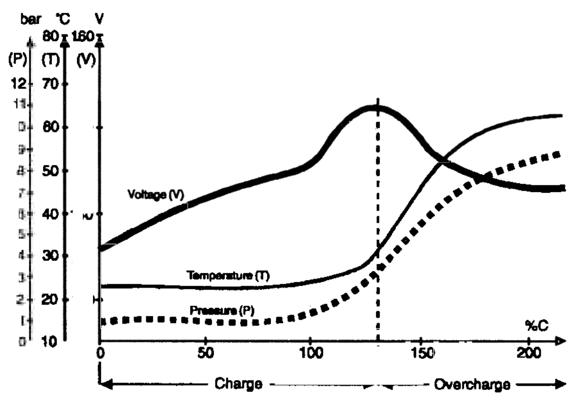

Fig 6. - NiCd Charge Characteristics

internal pressure from the gas generation would probably be the best indication of over-charge, a pressure switch in each cell is not a cost-effective solution. A temperature sensor is less expensive but still requires an added component, plus dealing with variations in ambient temperature and the effects of thermal resistance between the inside of the cells and a practical location for sensor placement. While battery voltage is the least definitive indication of charge, it does have the benefit of eliminating the need for any sensors. It can be used by observing that the negative temperature coefficient of a NiCd's voltage causes the voltage to drop as the temperature increases. While the change is small, sophisticated analog circuitry can determine when the increasing cell voltage begins to decrease. This is called the negative dV/dt technique and has successfully been used in recharging NiCd batteries in one hour or less.

NICKEL METAL HYDRIDE – This battery formulation is an extension of NiCd technology and shares many of its characteristics, but with several important differences. The major construction difference is that the anode of the battery is made from a metal hydride and, with the loss of cadmium, go many of the environmental concerns. (It should be noted that there has been some voicing of concern over the environmental effects of nickel, but thus far they have been muted.)

Recognizing the similarity to NiCd, it is easiest to discuss NiMH in terms of its difference with this earlier technology. One of the most positive benefits is that NiMH batteries will be substantially smaller and lighter than equivalent NiCd's. Also, a NiMH battery is not as susceptible to the memory effect. On the negative side of the ledger is higher cost, less capability to deliver high peak currents, greater risk from damage due to overcharging, and a higher self-discharge rate. (It should be noted that manufacturers are quick to point out that all these negative features can potentially be improved with increased manufacturing experience.)

The recharge process for a NiMH battery is also different in that it is exothermic throughout charging. With the internal temperature rising continuously, temperature measurements must be made even more carefully to catch the distinction between the gentle rise during charging and the more rapid rise with the onset of overcharge. In addition, there is little, if any, negative voltage change which makes -dV/dt sensors ineffective.

Since controlling the termination of high-rate recharge is almost exclusively performed for NiMH batteries using temperature as an indicator, many sophisticated algorithms have been developed for this task. In addition to ambient temperature (Which must be measured anyway since high-rate charging must not take place outside the range of −15°C to +40°C.), both the change in temperature (dT), and the change in slope of the temperature curve (dT/dt) have been used. A significant problem with all these techniques is that as charging proceeds, the battery's ability to accept charge diminishes. Trying to add additional charge then serves mainly to generate additional heat which further reduces charge acceptance. The result is that it is very difficult to return to more than 80% of full charge. This is so much of a problem that many manufacturers have taken to underrating their batteries as a defense against complaints from users who cannot achieve full capacity utilization.

LITHIUM ION – Since Lithium has an atomic weight of 6.9 – vs. 207 for lead – the prospect of substantial weight reduction has spurred extensive research in this field – research which is beginning to show significant results. Currently available Lithium batteries have approximately twice the energy density (W-hr/kg) than NiMH of similar capacity. In addition, the higher voltage of the Lithium cell (3.5 Volts nominal) could mean fewer cells in series to achieve a usable system voltage. That's the good news. Problems include a very critical dependency on charging voltage, a poorly regulated discharge curve which drops from 4.2V to 2.5V, and the fact that cells discharged below 2.5V would suffer permanent damage. While the self discharge rate of Lithium cells is much better than either of the nickel types, it still exists and therefore there is a finite limit to shelf life. However, as stated above, progress has been made and viable Lithium batteries are available today.

Because Lithium technology is still evolving, it is difficult to be very quantitative at any point in time. Lithium ion cells have used cobalt, carbon, or

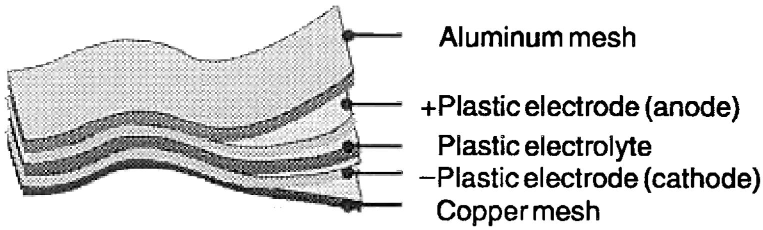

Fig 7. - Bellcore Lithium Polymer Battery

graphite in the cathode with varying performance. The recent introduction of a Lithium ion, metal-free polymer cell announced by Bellcore shows significant promise. This system, which is shown in Figure 7, uses a solid electrolyte and can be packaged in very thin configurations. Because of the bidirectional flow of Lithium ions between the electrodes, this structure is often called a "rocking chair" battery.

Charging a Lithium battery can be as simple as providing a current source with a voltage clamp; however, the critical balance between maximum capacity and over-voltage damage requires that the clamping voltage have a high degree of accuracy — perhaps as tight as 100 mV. At a normal charge rate, the battery will reach this 4.2V level with about 65% of the charge replaced. Now, however, at constant voltage, the charging current will diminish exponentially, requiring a significantly longer time to gain the last 35% to full charge. Faster charging can be achieved by using an initial higher voltage but this must be carefully engineered for the specific battery being used.

This voltage criticality makes series combinations of Lithium cells more difficult. As multiple cells are charged, each cell must be clamped at 4.2V while still allowing current to flow through the ones which are slower to reach full charge. Similarly, under discharge the voltage of each cell should be monitored so that the load can be removed when the weakest cell reaches 2.5V. For these reasons, it would appear that a single cell followed by a switch-mode boost converter would be preferred over series combinations. This would have the added advantage of being able to regulate the decreasing voltage as the cell discharges. A device proposed by Unitrode to accomplish this is shown in Figure 8.

This converter uses a unique synchronous rectifier which can be turned off to current flow in either direction. This allows it to serve as a conventional boost rectifier when the converter is operating and yet completely disconnect the load when the battery's minimum voltage has been reached.

ZINC AIR — This battery is different from all the others we have discussed in that instead of sealing the battery, this technology contains an air breathing cathode which is able to extract oxygen

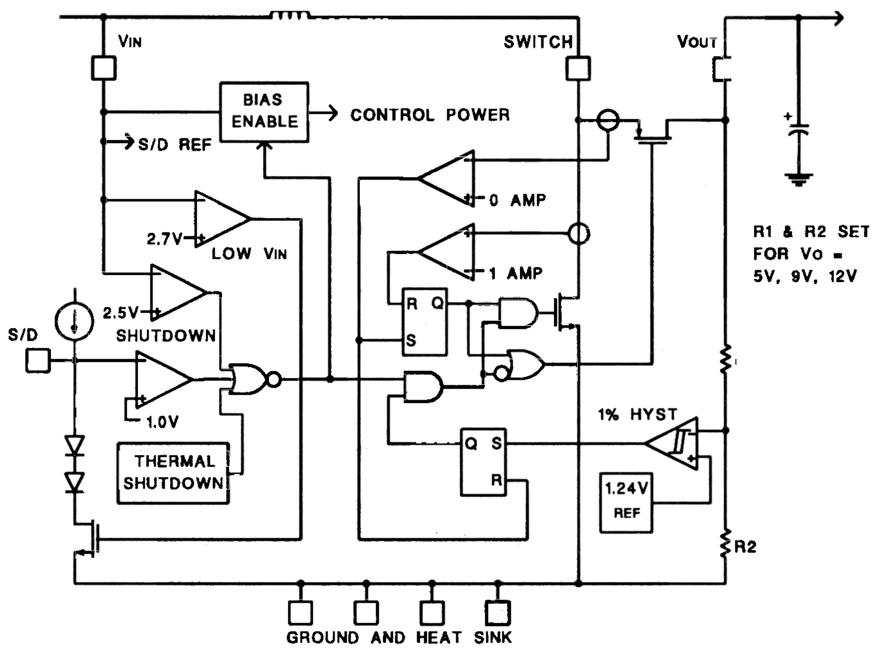

Fig 8. - The UCC3879 Lithium Battery Boost Converter

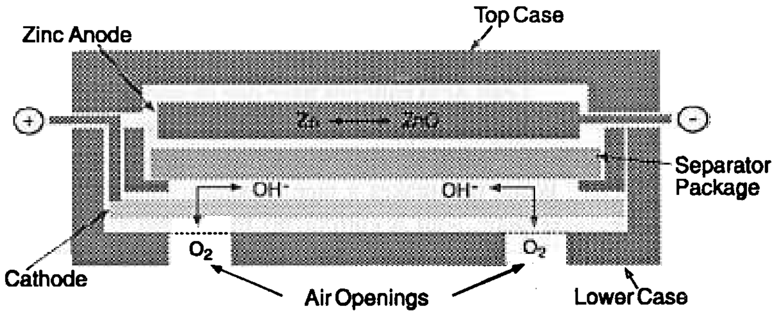

Fig 9. - The AER Zinc-Air Cell Design

from the air to produce the ionic flow in the electrolyte. Zinc forms the anode and the electrolyte consists of potassium hydroxide. As one might expect, the air valve is a critical part of this system. It must allow air to flow into the cells during discharge but seal off during charge and when the battery is not in use. AER Energy Resources claims to have solved this issue with a battery design offering an energy density of 155 Whr/kg, the highest of any we have reviewed. A cross section of their design is shown in Figure 9.

Present-day charging techniques use relatively low-rate, constant-current approaches. Fast-charge algorithms have yet to be developed. A voltage rise at full charge can be used as a termination indicator. With very low self-discharge, a float voltage or trickle current is neither needed nor recommended.

While there is much promise with Zinc Air technology — including the ability to achieve eight-hour operating time with a *color* notebook computer — there is too little experience to offer any conclusions as to the long term viability of this chemistry. However, it is interesting enough to warrant investigation as new applications arise.

Selection Considerations

If nothing else, the above discussion should have illustrated the degree of difficulty in selecting the optimum battery type for a specific application. And it should be noted that we have not even touched on electric vehicles. While the specific requirements for powering automobiles, and the multitude of battery chemistries proposed, are beyond the scope of this topic, it can be assumed that if these vehicles do go into high volume production, there will be spin-off battery developments which could impact all our portable power applications.

Table 1 presents a comparison chart of electrical characteristics for the batteries we have covered.

To summarize the most important features of each battery type, a list of positive and negative attributes is given in Table 2 as an aid in starting the selection process.

Table 1 - - BATTERY TECHNOLOGY COMPARISONS

ELECTROCHEMISTRY		Rechg Alk.	Silver Zinc	Lead Acid	Nickel Cad.	Nickel MH	Lithium Ion	Zinc Air
Nominal Cell Voltage	(V/cell)	1.5	1.5	2.0	1.2	1.2	3.5	1.2
End of Life Voltage	(V/cell)	0.9	1.25	1.7	1.0	1.0	2.5	0.9
Energy Density	(W-hr/kg)	75	110	35	50	60	110	150
	(W-hr/ltr)	200	220	80	100	130	180	160
Self-Discharge Rate	(%/month)	0.5	1	2	15	30	1	5
Cycle Life	(25%dischg)	100	100	1200	2000	500	1000	100
	(100%dischg)	25	50	300	500	500	300	25
Cost/W-hr (*Estimate)	($/W-hr)	0.33	2.00	0.50	1.00	1.50	1.00*	1.25*

Table 2 - BATTERY FEATURES

RECHARGEABLE ALKALINE		
	Best:	Not clear
	Worst:	Limited cycle life
SILVER ZINC		
	Best:	High reliability
	Worst:	High cost
LEAD ACID		
	Best:	Mature, Long storage life, Low cost
	Worst:	Heaviest
NICKEL CADMIUM		
	Best:	Mature, High peak current, Large cycle life
	Worst:	Heavy, Memory effect
NICKEL METAL HYDRIDE		
	Best:	Lighter, Environment safe
	Worst:	Cost, Self discharge, Complicated charging
LITHIUM		
	Best:	Light weight, High voltage
	Worst:	Critical charging, Cost
ZINC AIR		
	Best:	Lightest weight
	Worst:	Not in production

Charger Examples

In discussing battery chargers, it should be understood right at the beginning that charging a battery over a long period of time represents what is commonly called a "no brainer". With the possible exception of Lithium, holding the charge current to less than C/10 allows for relatively safe and simple charging. The only problem is waiting the 12-16 hours it takes, and most of the innovative charging techniques which have been developed are just to speed up the process. The problem is that fast charging is dangerous to the battery — and sometimes to the user. Doing it safely and reliably is where all of the engineering has been and must be applied. With that preamble, we will discuss some examples.

A Multi-State Fast Charger for Sealed Lead Acid Batteries

Lead Acid batteries have one characteristic useful in recharging: the battery voltage takes a relatively sharp jump upward when overcharge commences. While this makes a nice indicator, unless charging is done with a current no more than C/100, this indication will occur at less than 100% capacity. For a fast rate — C/5, for example — this indication occurs at only 80% capacity. To reach full capacity, the battery must be held in the overcharging state for some additional period of time. Once full capacity is achieved, a lower float voltage must then be maintained to make up for self discharge. Properly applied, this float voltage may be left on the battery for the full life of the battery — 6 to 10 years — however, the value is fairly critical. Manufacturers claim that a 5% error in this voltage level can halve this expected life. Making it more difficult is the fact that there is a –4.0 mV/°C temperature coefficient to the optimum float voltage level.

Solving this problem is made easier with the UC3906 Lead Acid Battery Charge Controller shown in Figure 10 as applied to a linear 3 A-hr charger.

This basic circuit can be set up to charge a single cell or as many as 12 in series, and higher capacities can be accommodated by scaling up the external power device. The only limitation is that the input DC voltage must be at least two Volts higher than the maximum battery voltage.

The circuit provides four-state charging as shown in the state diagram of Figure 11. These states are described as follows:

State 1: A trickle current is applied to a completely discharged battery until a voltage, Vt, is reached. Vt is set low enough so that if a cell is shorted, high rate charging will not commence.

State 2: The bulk charge state where constant current, Imax, is applied to rapidly charge the battery into the overcharge condition. Some 80% of the charge is returned during this state.

State 3: When the voltage rises past V12, this state is entered where the charger now applies a constant voltage, Voc. With this fixed over-voltage, final charging is accomplished as the rising battery

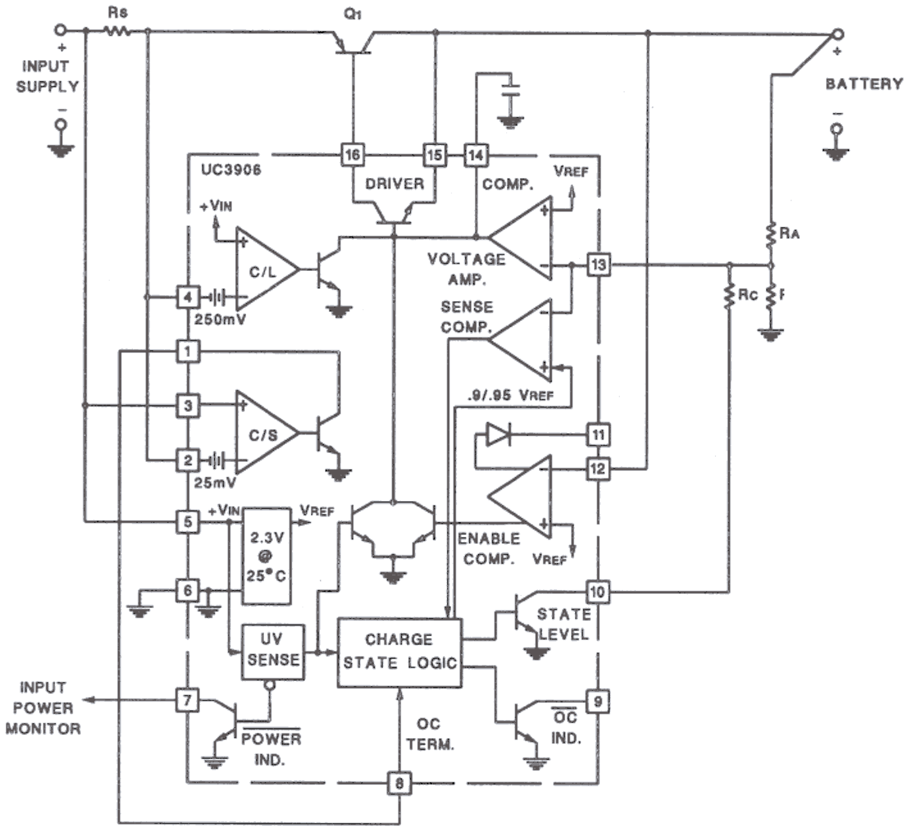

Fig 10. - A Four-State Float Charger Using the UC3906

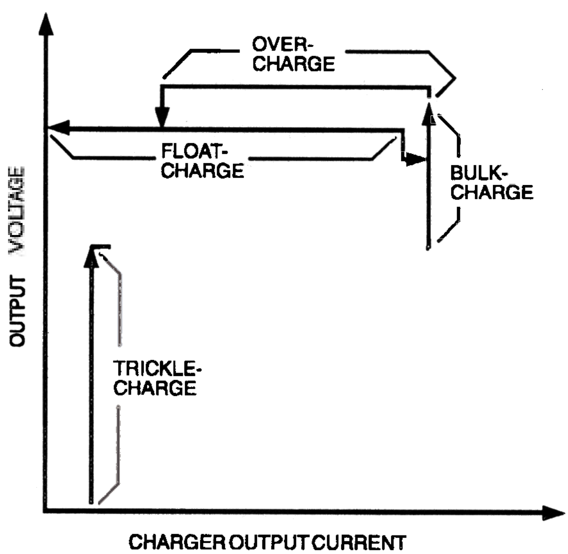

Fig 11. - Four-State Charge Algorithm

charge reduces the current accepted to a minimum value, Ioct, which triggers the float voltage state. An external timer can also be used in parallel to limit the time allowed for over-voltage charging.

State 4: In this float voltage state, current will be whatever is necessary to maintain maximum capacity. If the battery should become loaded, when the voltage falls below V31, the charger will switch back to State 2 and reapply Imax, initiating a new cycle.

It should be noted that the voltage reference within the UC3906 has a built-in −4mV/°C TC so that all voltage thresholds will track the requirements of the lead acid battery. Of course, this means that the UC3906 must be at the same temperature as the battery and the charger power stage must be designed so that it does not add any self heating to the controller.

For details in designing this type of charger, see

Unitrode Application Note U-104. A more sophisticated and efficient application of this controller is described in Application Note U-131 which uses average current-mode control to command a high-frequency step-down switching regulator to provide the same multi-state charging algorithm.

A Temperature-Servo Charger for NiMH and NiCd Batteries

A characteristic prevalent in all batteries, but particularly troublesome with NiMH and NiCd types, is the fall off in charge acceptance which occurs during charging. This is why one needs to replace as much as 160% of the rated capacity to fully recharge a battery. This would not be quite so bad were it not for the fact that the additional 60% of input power is dissipated as heat. Batteries make poor heat sinks so without some considerable care, or a long time duration, this added heat could raise battery temperature to the point of destruction. The relationship between battery capacity, charge acceptance, and temperature for a typical NiMH battery being charged at a safe level of C/10 is shown in Figure 12.

All present-day "Fast Charge" controllers use an initial high charging current — typically between C and 4C — while employing one or multiple charge termination techniques to determine the onset of "end of charge". While these approaches may be *safe* as far as the battery is concerned, the point of termination that is detected is *far* from the 100% charged point, in spite of claims to the contrary. For example, Figure 13 shows the use of a typical two-slope commercial charger designed to initially charge at the 4C rate. (Note that in this curve and the ones to follow, the time scale has been reduced.)

While one would assume that at 4C, full capacity would be reached in some 20 minutes, such is far from the case. Note that during this high-rate state, charge acceptance dropped by close to 40% and with this amount of the input power now generating heat, battery temperature rose some 15°C. With this much temperature rise, the charger must now drop to a C/10 rate, a transition which the charger typically reports as "full charge". At this rate, however, an additional 6-7 hours will be required to achieve true 100% capacity. Or, more likely, the user returns to work with a battery at 80% capacity.

Since the conditions which dominate during the "Top Off" phase of battery charging are thermal in nature, all fast chargers necessarily use some form of temperature sensing — either as a primary or a backup technique — for terminating the high-current charge state. However, they then ironically abandon those techniques during the final phase of charging where thermal management is much more critical. And thus, *fast charging* has become synonymous with *partial charging*.

Unitrode has proposed as a solution to this problem, the UCC3905 Servo-Charge™ Battery Charge

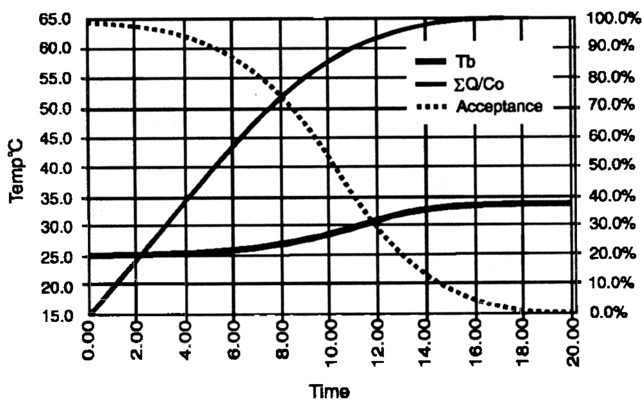

Fig 12. - NIMH Charge Characteristic at Safe but Slow C/10 Rate

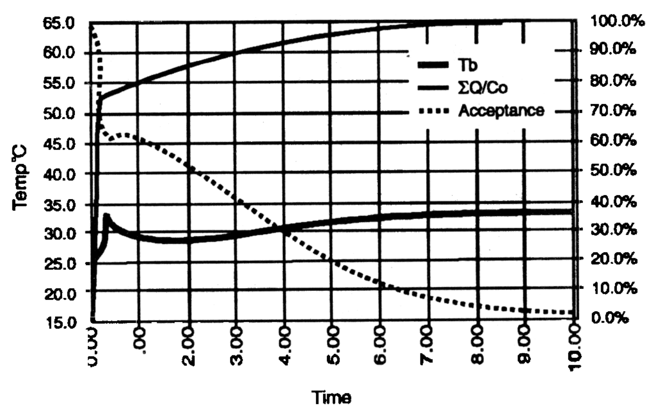

Fig 13. - NiMH Charge Characteristic at 4C Charging Rate

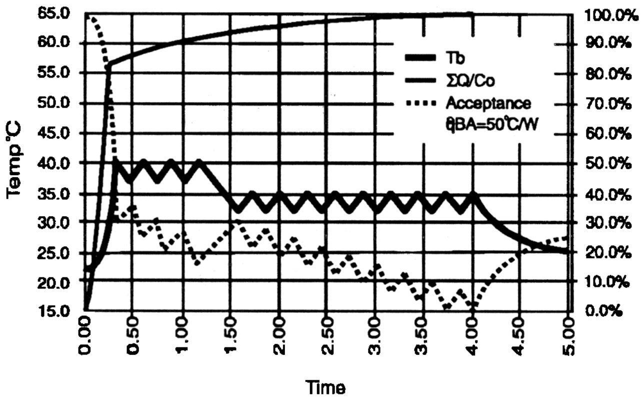

Fig 14. - UCC3905 Applied in Same Environment as Fig. 14

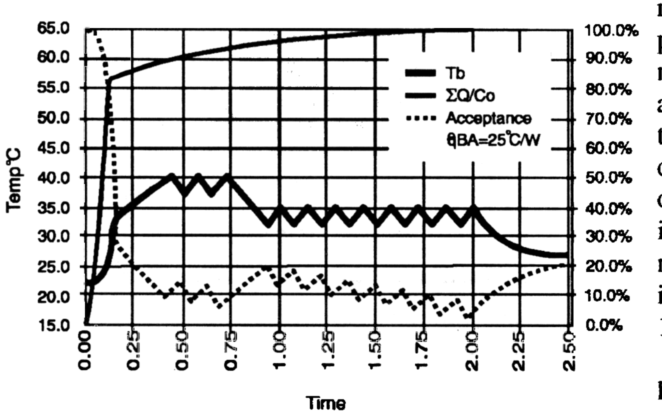

Fig 15. - Faster Charge Adaptation with Battery Heat Sinking

Controller. This device is designed to provide both a controlled high-current charging source to achieve rapid recovery to "indicated" full capacity, followed by a multi-state adaptive temperature control to reach a true 100% capacity in the shortest possible top-off time. Throughout the process, high-current pulses with a constant amplitude are applied to the battery — but the duty-cycle, or pulse width, is adjusted to control the average current and thus the charging rate. Since temperature control is the basis for this algorithm, a temperature sensor within the battery pack — typically a 10 kOhm thermistor — is a necessary element.

In the high-rate state, the UCC3905 provides current pulses which can be programmed for a C, 2C, 4C, or 6C rate. Like most other sophisticated high-rate chargers, several parameters are monitored while fast charging, and this state will be terminated when any one exceeds defined limits. These parameters include: open-circuit voltage, rate-of-change of voltage, absolute temperature, rate-of-change of temperature, and time. Time, in the case of the UCC3905 is measured in "C" units where "C" is 100% rated capacity and, if not terminated earlier from one of the other parameters, this state will end when "C" = 1.0. For example, if the charging rate is 4C, this high-rate state will end in 15 minutes.

What happens next is unique to the UCC3905. Instead of just dropping to a low rate, the pulse width of the charging current pulses is controlled in a servo feedback loop to maintain a constant battery temperature. This is actually done in two states — The first to maintain a battery temperature of 40°C for a time duration of 0.3 "C" units, followed by a period of 0.6 "C" units wherein the battery temperature is held to 33.5°C. Of course, all the other safety mechanisms still apply. The result of this charging algorithm is shown in the chart of Figure 14.

From this chart it can be seen that the battery has reached 90% capacity in one hour instead of the 3 hours it would take in more conventional "fast" chargers. If it were possible to provide an improved thermal environment for the battery — such as with heat sinking or air flow — the UCC3905's algorithm would automatically adapt and potentially yield the characteristics shown in Figure 15 which shows obtaining 90% capacity in 12 minutes.

The block diagram of the UCC3905 is shown in Figure 16 but the data sheet should be referenced for additional details in its operation.

Smart Batteries

It seems that everything we build these days is getting smarter, so why shouldn't batteries. As battery cells are combined into battery packs, it's clear that additional components could be incorporated with some benefit. An obvious first step is the inclusion of a temperature sensor whose need has

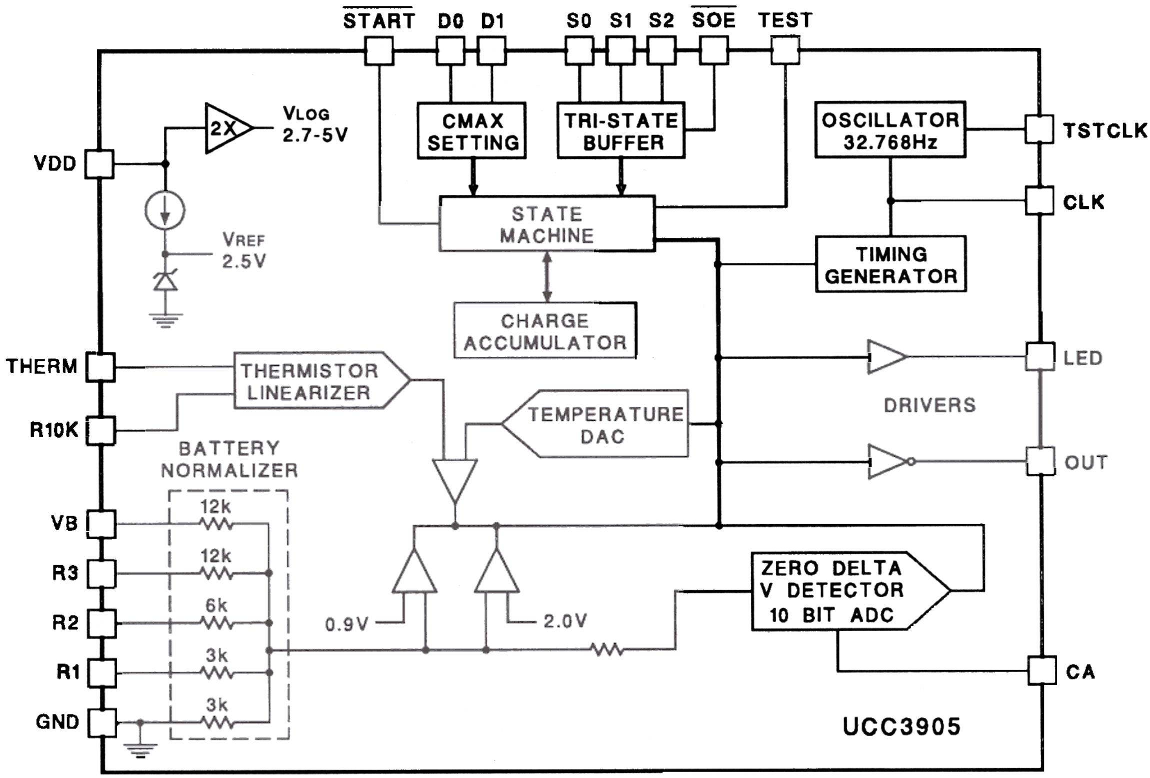

Fig 16. The UCC3905 NiMH Servo-Charge™ Controller

already been discussed. Many would also recognize the value of knowing how much capacity remains as the battery is utilized and, particularly when batteries are removed or exchanged in the application, a reasonable place to consider locating a "fuel gage" would be within the battery pack.

Intel and Duracell have recently announced a plan to carry this thought considerably beyond this point with the "Smart Battery Model" shown in Figure 17.

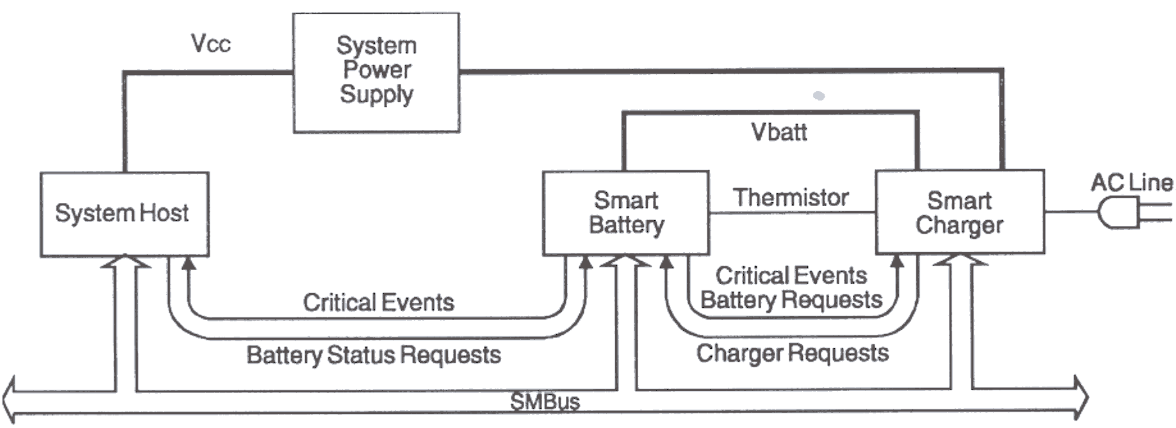

Fig 17. - The Intel "Smart Battery" System Model

This ambitious program uses a two-wire System Management Bus to tie the battery, the charger, and the load together with the intent of allowing information flow which could include:

- Allowing the user to know remaining battery life, time to charge, and any faults.
- Allowing the battery to know the load's power management requirements to anticipate future needs and to record all that has happened to it in the past.
- Allowing the charger to know the type of battery and what its charging requirements are.
- Allowing the manufacturer to electronically identify the battery as well as learn how it has been treated.

And, of course, with this capability, much more is possible once the digital interface and adequate processing capability has been added to the battery pack. While all this is certainly possible, one must not forget "Basic Battery Truth Number One", namely: All batteries will eventually die. How much value do we want to add to an item which has a finite life? At this point, it's too soon to tell.

A PC-based Battery Charger Emulator

In determining an optimum charging algorithm, one cannot escape the need to accumulate empirical data on actual batteries. The only way to thoroughly evaluate a proposed charging routine is by evaluating the performance of a battery exercised under that routine. Therefore, a system for easily implementing a variety of experimental charging approaches, coupled with the ability to repetitively discharge the battery in a controlled way with data gathering capabilities, becomes a powerful tool for designing battery management systems. In the course of developing the UCC3905, Unitrode has developed such a system, the definition of which will be offered to users who desire to implement and conduct their own experiments.

The system architecture for this emulator is shown in Figure 18.

The elements of this system include the following:

- A 386/486 PC including a Data Acquisition card.
- A programmable current source
- A test fixture to interface with an optional controller IC and its associated circuitry.
- A battery connection fixture together with thermistor connections.

With this system, all the set points of the charge algorithm may be assigned and used to charge a test battery, followed by a definable discharge sequence where the actual battery capacity may be measured by plotting a voltage discharge curve. Repetitive cycles will provide information both on the true capacity recovered by charging and on the charge algorithm's impact on long-term cycle life.

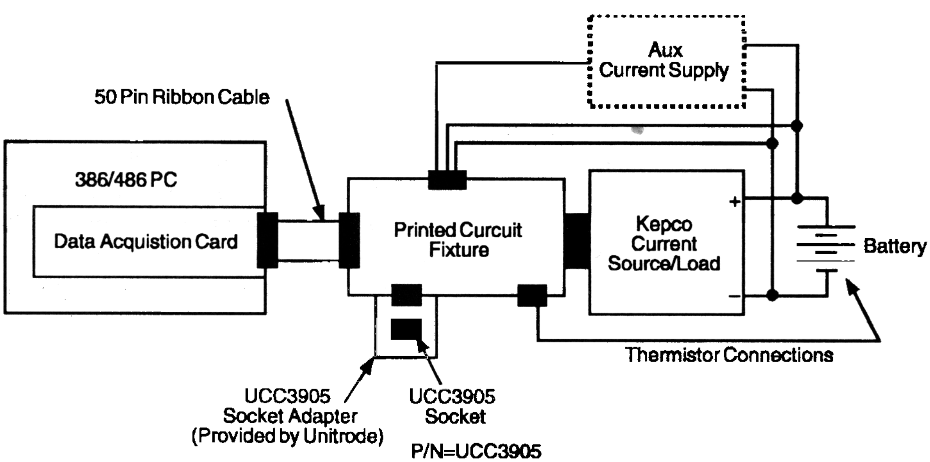

Fig 18. UCC3905 Charger Emulator Configuration

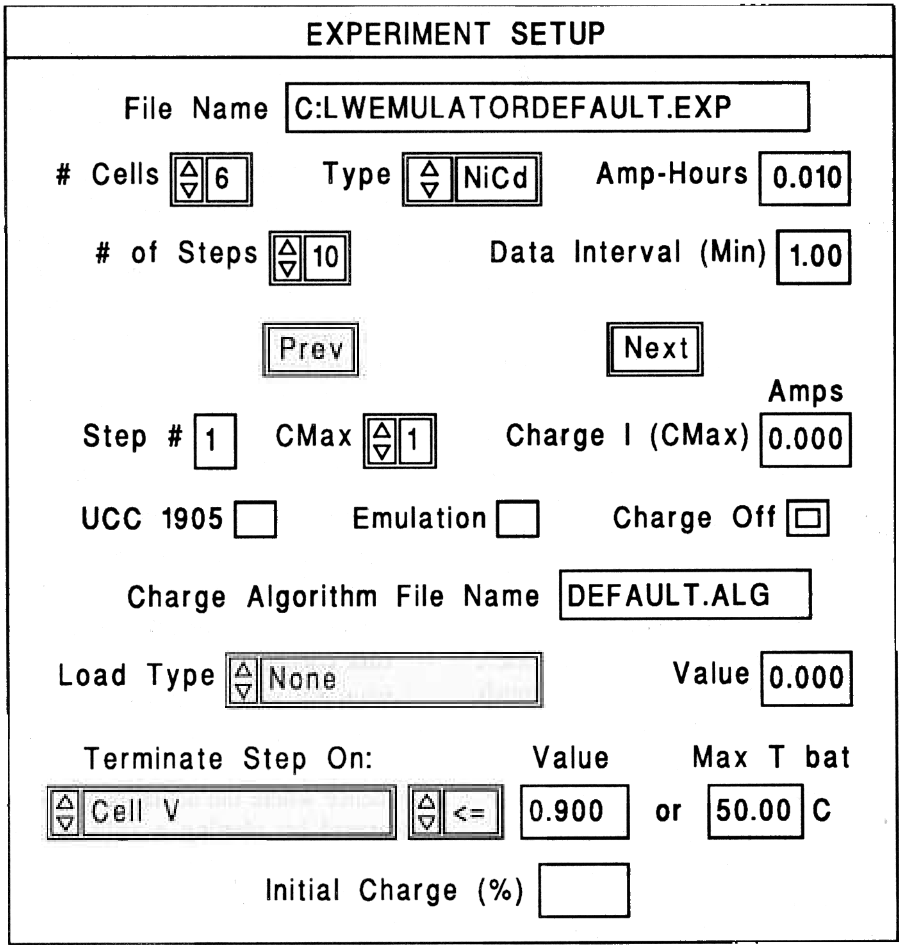

Fig 19. UCC3905 Emulator Setup Screen

Figure 19 shows the experimental setup screen where inputs to define the type and size of the battery under test can be made, along with the definition of the various set points for a particular test. This emulator can be used either to experiment with variations to the charge algorithm or, with insertion of a UCC3905, as a data gathering tool to evaluate the performance of this device under different test conditions and with different batteries.

The status screen shown in Figure 20 provides real time information during the progress of an experiment by indicating the sequencing of the charging state along with instantaneous measured values of battery parameters. This data is recorded for later generation of graphical performance curves.

Regardless of the particular method utilized, the number of variables involved in any charging system make the use of a data gathering system, such as this emulator, an extremely valuable tool in reaching a positive conclusion as to the performance of any proposed charging system and battery type.

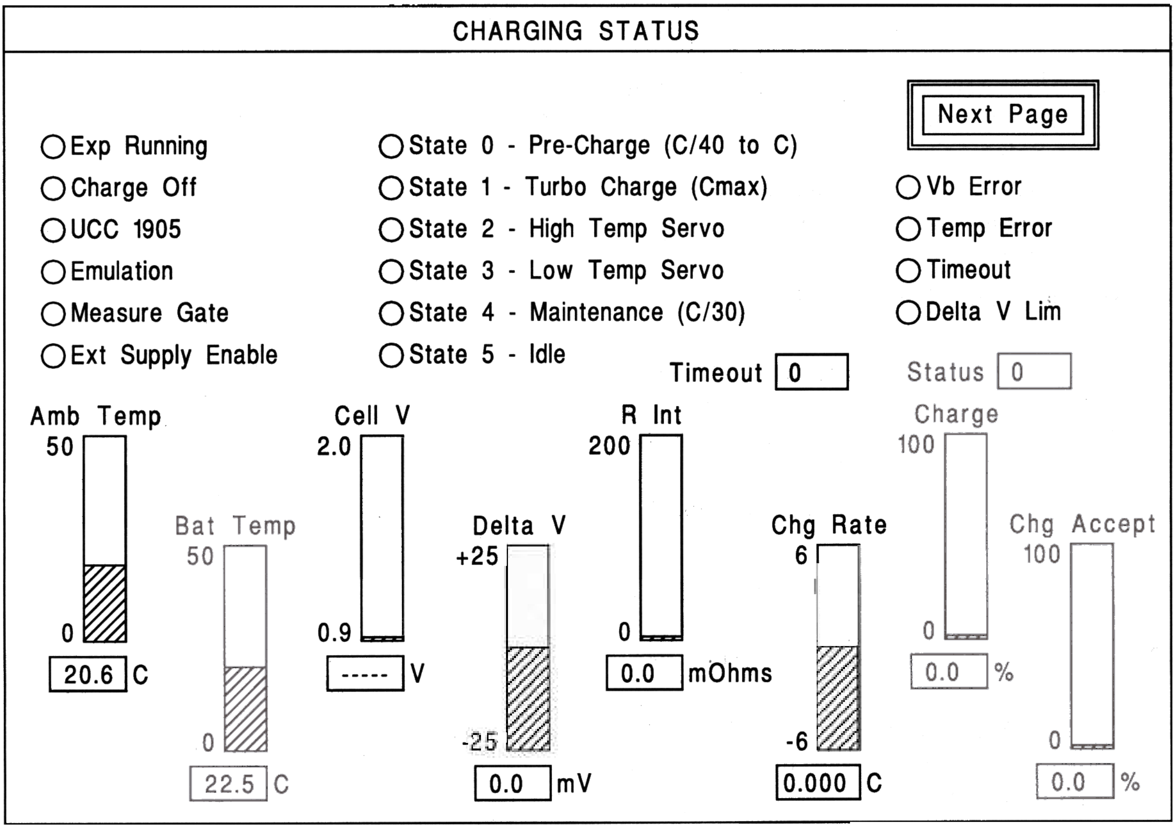

Fig 20. - UCC3905 Emulator Status Screen

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