HANDHELD CALCULATOR BATTERY SYSTEMS

INTRODUCTION

Batteries suitable for handheld calculator applications can be categorized into two groups: primary cells and secondary cells. Primary cells cannot be recharged efficiently or safely and are used in "throw away" systems, i.e., the end user must replace the calculator batteries at end of life. Secondary cells can be recharged after being discharged under specified conditions.

PRIMARY CELLS

Carbon-zinc and alkaline are the best known non-rechargeable cells available for calculators. Carbon-zinc cells are low cost, but have relatively high internal resistance characteristics that reduce efficiency under high current drain conditions. They are widely available around the world in a variety of voltages, capacity and form factor options. Alkaline cells offer 300 to 400 per cent more capacity than carbon-zinc batteries of the same size and have excellent characteristics under the high drain conditions typical of LED display calculators. Both types have voltage discharge curves that fall gradually over life. Shelf life for alkaline is good, carbon-zinc poor; an important parameter if batteries are to be shipped with the finished calculator and may sit on warehouse or display shelves for unknown periods of time. Not surprisingly, alkaline cells are also three to four times more expensive than carbon-zinc. Silver oxide batteries have been used in throw-away calculator applications to achieve a more desirable form factor. Although replacements are available (the cells are often used in hearing aids and cameras) the high current drain inefficiency of the cell results in poor utilization of available capacity, and battery life is short.

SECONDARY CELLS

Nickel-cadmium batteries have become the standard for rechargeable systems. They exhibit relatively constant discharge voltages and can be recharged many times. Internal resistance is low so they are capable of supplying high peak currents.

Figure 1 indicates the discharge characteristics of carbon-zinc, alkaline and nickel-cadmium cells.

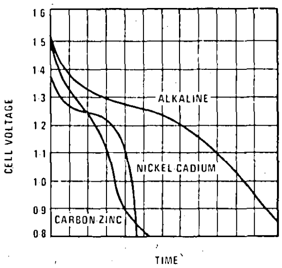

Figure 1. Comparison of Discharge Characteristics

THE SIMPLEST SYSTEM – A 9 V BATTERY

Most National Semiconductor calculator circuits use a P-channel, metal gate MOS process with enhancement and depletion mode transistors. They are designed to operate directly from a nine volt alkaline or carbon-zinc battery. Operating voltage range is 6.5 V to 9.5 V. A nine volt battery is simply six series cells with characteristics similar to those shown in Figure 1, allowing an end-point voltage for each cell of just under 1.1 V for a worst-case calculator.

A complete calculator using a nine volt battery is shown in Figure 2. This is undoubtedly the simplest battery system available for a low cost calculator, as well as being the most efficient. The current required to drive the display and MOS circuit comes directly from the battery without any conversion of voltage.

Battery life estimates are straightforward. Assuming a nine digit calculator using the National MM5760 slide rule chip, and five "8s" as a typical display condition, it is easy to calculate total battery current drain and battery life:

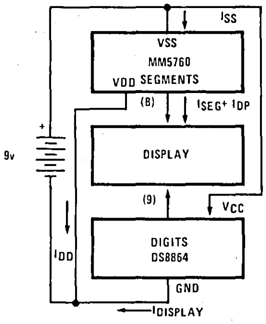

Figure 2. Power Supply Current for 9 V Calculator

Referring to Figure 2 and using typical values from the 5760 data sheet,

$$I_{DISPLAY} = I_{SEG}(\text{Ave}) + I_{DP}(\text{Ave})$$

$$= (I_{SEG}) \begin{pmatrix}\text{no. of segments}\\ \text{on per digit}\end{pmatrix} \begin{pmatrix}\text{no. of digits}\\ \text{on per word}\end{pmatrix} \begin{pmatrix}\text{Digit Duty}\\ \text{Cycle}\end{pmatrix} + I_{DP}$$

where I_{SEG} = Peak Segment Current

$$\text{Digit Duty Cycle} = \frac{(\text{Digit Time}) - (\text{Segment Blanking Time})}{(\text{Word Time})}$$

$$= \frac{70\,\mu s - 4.5\,\mu s}{650\,\mu s} \sim 0.100$$

Therefore, for a display of five "8s:"

$$I_{DISPLAY} = \left(\frac{8.5\text{ mA}}{\text{Seg}}\right)\left(\frac{7\text{Seg}}{\text{Digit}}\right)(5\text{ digits})(0.100)$$

$$= 29.75\text{ mA}$$

$$I_{BATTERY\,DRAIN} = I_{SS} = I_{DD} + I_{DISPLAY}$$

$$= 8.0\text{ mA} + 29.8\text{ mA} = 37.8\text{ mA}$$

Battery life is a function of the battery being used, of course, and its capacity. An alkaline 9 V battery has a capacity of approximately 550 mA-hr.

$$\text{Battery Life} = \frac{\text{Battery Capacity}}{I_{\text{BATTERY DRAIN}}} = \frac{550 \text{ mA-hr}}{37.8 \text{ mA}}$$

$$= 14.3 \text{ hr, typical}$$

As a comparison, a carbon-zinc 9 V battery is rated at only 125 mA-hr, giving a typical battery life of only 3.24 hr.

SOMETIMES SIMPLEST ISN'T BEST

In some cases it is not advantageous to design the calculator with a 9 V battery system. If the calculator is to be marketed in an area of the world where 9 V replacements are difficult to find, or a unique form factor is required to optimize overall calculator shape or size, alternate battery systems may be preferable.

Rechargeable systems are usually more cost effective as two, three or four cell systems. If it is decided to market both throw-away and rechargeable models of the same calculator, the battery system should allow the use of all the same hardware in both models; this means both primary and secondary batteries should be essentially the same form factor and voltage. N, AA and AAA cells all meet that requirement, and are often used in handheld calculators. Alkaline N and AAA cells are usually rated around 550 mA-hr and AA at over 1500 mA-hr. Nickel-cadmium cells supply about one third the capacity of physically equivalent alkaline cells, e.g., AA nickel-cadmium cells are rated about 500 mA-hr.

THE TWO CELL SYSTEM

Figure 3 shows the MM5760 in a two cell battery system. All the display and MOS current must be converted up to the 6.5 V to 9.5 V range needed to drive the MM5760.

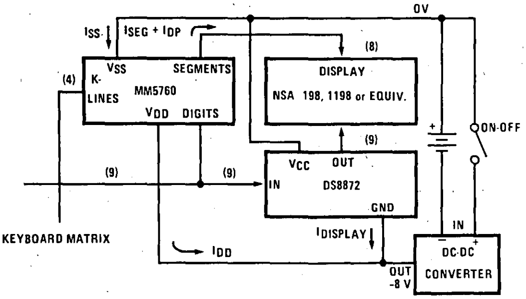

Figure 3. Two Cell Battery System

The DC-DC converter must supply greater than V_{SS} − 6.5 V with an input voltage range of 2.2 V to 2.5 V for nickel-cadmium cells or 2.2 V to 3.0 V for alkaline. Battery drain will be increased due to the voltage conversion and efficiency of the converter.

$$I_{\text{BATTERY DRAIN}} = (I_{DD} + I_{\text{DISPLAY}}) \frac{(V_{\text{CONVERTER}})}{(V_{\text{BAT}})(E_{\text{FF CONVERTER}})}$$

$(I_{DD} + I_{\text{DISPLAY}})$ will be the same as the 9 V case. Assume the DC-DC converter has a nominal output voltage of 8.0 V, and an efficiency of 75%:

$$I_{\text{BATTERY DRAIN}} = (37.8 \text{ mA})\left(\frac{8.0 \text{ V}}{2.6 \text{ V}}\right)\left(\frac{1}{0.75}\right) = 155.1 \text{ mA}$$

If two AA alkaline cells were used, average battery life would be (1500 mA-hr/155.1 mA), or just over 9.6 hours; 500 mA-hr nickel-cadmium batteries would typically give 3.2 hours between recharges.

THREE CELLS INCREASE EFFICIENCY

Three cell systems provide a significant improvement in efficiency by reducing the converted power compared to a two cell system. Three cells have a minimum operating voltage of roughly 3.3 V. By using a bipolar segment driver chip to supply the required segment current at a low voltage, the display current loop can be separated from the higher-voltage MOS current path and operated directly off the three cell battery system. Now the low MOS supply current is the only component magnified by the voltage conversion, and the total power efficiency is greatly enhanced.

Figure 4(a) schematically shows the display interface of a three cell system. The DS8867 Segment Driver is guaranteed to supply a minimum of 8 mA of peak segment current to the LED display at an output voltage of 2.3 V (or higher) with respect to the negative terminal of the battery. The 2.3 V must be divided between the LED and "ON" digit driver output voltage; single output transistor (non-darlington) types of bipolar digit drivers such as the DS8868, DS8873, DS8973 or DS8879 have worst-case "ON" voltages of 0.5 V or less. With both worst-case digit and segment drivers, the LED will have 2.3 V − 0.5 V = 1.8 V as an "ON" voltage. GaAsP displays like the NSA1198 and NSA1298 show typical voltage drops of around 1.65 V at 10 mA of segment current on their data sheets. (If all worst-case components, including the LED were combined, a reduction in peak current could occur at minimum battery voltage.) For nine digit calculators using the NSA1198 and NSA1298 displays, the minimum peak current required for reliable operation is 3.0 mA/segment and 5.0 mA/segment, respectively, well below actual limits even with worst-case components.

To guarantee adequate digit output signals for scanning the keyboard, external series resistors (~ 2.4k) would be required if DS8873 digit drivers were used rather than the DS8973. Calculators requiring a shift driver, such as the MM5784 or MM5791, use a DS8879 digit driver in three cell systems.

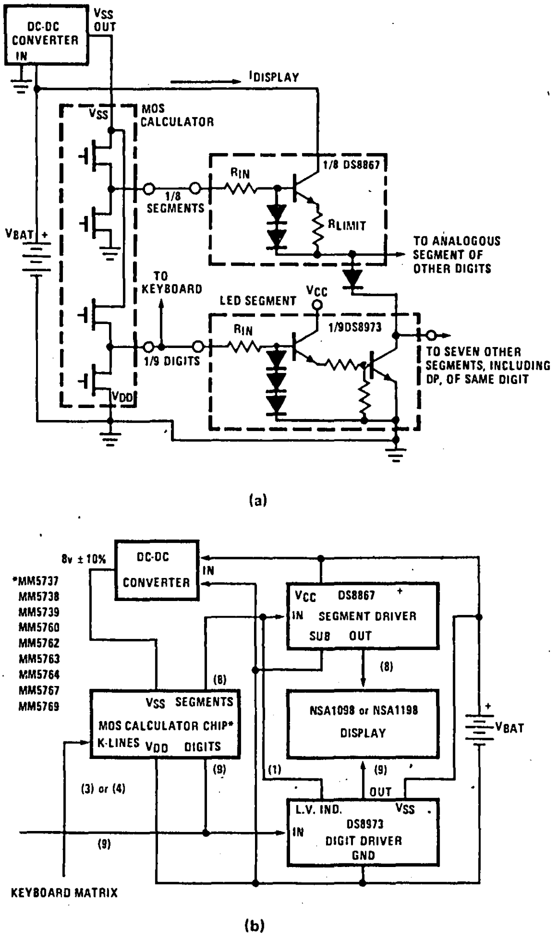

Figure 4 (a) Schematic Diagram, and (b) Block Diagram

With the exception of the MM5758 which is designed specifically to operate with a three cell battery system, all other National Semiconductor single chip calculators have low impedance segment output buffers suitable for driving LEDs directly. In a three cell system they will be capable of over-driving the DS8867. Typical input current to the DS8867 is about 1.5 mA per segment, which unfortunately must be converted up to the V_{SS} supply and therefore does impact battery life to some degree.

Typical battery drain for a display of five "8s" in a three cell system is:

$$I_{BAT} \cong \left\{\left[I_{DDMOS} + (I_{SEG\,DRIVE\,MOS})\left(\begin{matrix}\text{Digit Duty}\\ \text{Cycle}\end{matrix}\right)\left(\begin{matrix}\text{no. of}\\ \text{segments on}\end{matrix}\right)\right]\cdot\frac{V_{CONVERTER}}{V_{BAT}\cdot E_{FF\,CONVERTER}} + I_{SEG\,BAT}\left(\begin{matrix}\text{Digit Duty}\\ \text{Cycle}\end{matrix}\right)\cdot\left(\begin{matrix}\text{no. of}\\ \text{segments on}\end{matrix}\right)\right\}$$

$$I_{BAT} \cong \left\{\left[8\text{ mA} + (1.5\text{ mA})\left(\frac{5}{9}\right)(7)\right]\frac{8.0}{(3.6)(0.75)} + (17\text{ mA})(0.1)(5\text{ digits})\left(\frac{7\text{ seg}}{\text{Digit}}\right)\right\}$$

$$= 100.49\text{ mA}$$

Using three AA alkaline cells would give a battery life of (1500 mA-hr/100.5 mA), or almost 15 hours; a 56% improvement over the two cell system for the additional cost of the DS8867 and an additional battery. 500 mA/hr ni-cad cells would provide 5.0 hours of continuous life. Note that this extended battery life is with higher display current than the two cell system, which will result in a brighter display as an added bonus.

FOUR CELL SYSTEM

A four cell battery system offers even higher power efficiency than the three cell system and the additional battery cost is offset somewhat by the removal of the DS8867. If the DC-DC converter output voltage is regulated between V_{SS} - 7.5 V and V_{SS} - 9.5 V, segments can be driven directly (Figure 5). Figure 6 shows the system diagram.

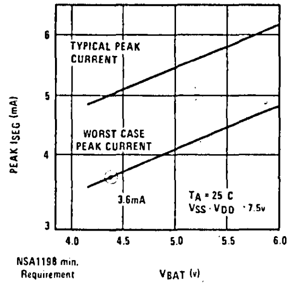

Figure 5. Guaranteed Peak Display Current vs. Battery Voltage in a Four Cell Battery System.

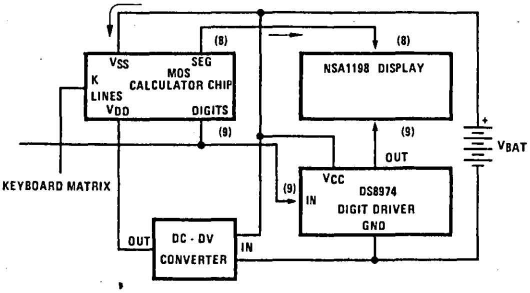

Figure 6. Four Cell Battery System

Like the three cell system, only the calculator supply needs to be converted up from the battery voltage. The display current flows in a loop from the positive terminal of the batteries, through V_{SS} and the segment buffers of the calculator chip to the LED, then the digit driver and back to the negative side of the batteries.

Battery drain current with five "8s" displayed is:

$$I_{BAT} = I_{DDMOS} \left(\frac{V_{CONVERTER}}{V_{BAT} \cdot E_{FF\,CONVERTER}} \right) + I_{DISPLAY}$$

$$\cong (10\text{ mA}) \left[\frac{8.75}{(4.8)\,(0.75)} \right] + \left(\frac{8.5\text{ mA}}{\text{seg}} \right) \left(\frac{7\text{ seg}}{\text{Digit}} \right) (5\text{ Digits})\,(0.1)$$

$$= 54.0\text{ mA}$$

Using four AA cells would give a battery life of at least (1500 mA-hr/54.0 mA), or almost 28 hours of continuous use. Four smaller capacity cells could be used to improve the form factor of the finished calculator and still maintain a reasonable battery life. For example, four alkaline N cells would give almost 10 hours of operation.

Table 1.

No. of Battery Cells	Calculator Type	Segment Driver	Digit Driver	DC-DC Converter	Typical Battery Life with AA Alkaline Cells
2	Group A	None	DS8872	$2.0\text{ V} \leqslant V_{IN} \leqslant 3.0\text{ V}$ $6.5\text{ V} \leqslant V_{OUT} \leqslant 9.5\text{ V}$ $I_{OUT} \leqslant -125\text{ mA}$	9.6 hours
2	Group B	None	DS8874	$2.0\text{ V} \leqslant V_{IN} \leqslant 3.0\text{ V}$ $6.5\text{ V} \leqslant V_{OUT} \leqslant 9.5\text{ V}$ $I_{OUT} \leqslant -125\text{ mA}$	7.7 hours
3	Group A	DS8867	DS8872 or DS8973	$3.0\text{ V} \leqslant V_{IN} \leqslant 4.5\text{ V}$ $7.2\text{ V} \leqslant V_{OUT} \leqslant 8.8\text{ V}$ $I_{OUT} \leqslant 20\text{ mA}$	15.0 hours
3	Group B	DS8867	DS8879	$3.0\text{ V} \leqslant V_{IN} \leqslant 4.5\text{ V}$ $7.2\text{ V} \leqslant V_{OUT} \leqslant 8.8\text{ V}$ $I_{OUT} \leqslant -20\text{ mA}$	15.0 hours
3	MM5758	DS8867	DS8868	$3.0\text{ V} \leqslant V_{IN} \leqslant 4.5\text{ V}$ $7.2\text{ V} \leqslant V_{OUT} \leqslant 8.8\text{ V}$ $I_{OUT} \leqslant -25\text{ mA}$	14.5 hours
4	Group A	None	DS8872 or DS8974	$4.4\text{ V} \leqslant V_{IN} \leqslant 6.0\text{ V}$ $-7.5\text{ V} \leqslant V_{OUT} \leqslant -9.5\text{ V}$ $I_{OUT} \leqslant 20\text{ mA}$	28.0 hours
4	Group B	None	DS8876	$4.4\text{ V} \leqslant V_{IN} \leqslant 6.0\text{ V}$ $-7.5\text{ V} \leqslant V_{OUT} \leqslant -9.5\text{ V}$ $I_{OUT} \leqslant 20\text{ mA}$	23.5 hours
9 V	Group A	None	DS8873 or DS8864	None	14.0 hours
9 V	Group B	None	DS8874	None	11.3 hours

Group A Calculators

MM5737
MM5738
MM5739
MM5760
MM5762
MM5763
MM5764
MM5767
MM5769

Group B Calculators

MM5784
MM5791