Application Note

Rechargeable Battery Pack State Of Charge Indicator Using SAA1500T

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Summary:

The state of charge indicator described in this Application Note can be incorporated into almost any (three or more cell) rechargeable battery pack. The indicator counts recharge and discharge energy to provide the user with an elegant six segment LED gauge of remaining battery capacity, together with indication of recharging. Circuit options include an LCD display and output for an audible warning device.

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1. INTRODUCTION - STATE OF CHARGE INDICATION

State of charge indication is an important and useful addition to any rechargeable battery pack for a variety of reasons. An underlying problem is the common tendency to recharge batteries many times more often than actually necessary. People waste time and effort in this way because they are always afraid of being caught out with empty batteries. State of charge indication helps to overcome this problem and brings other benefits such as:

- Increased battery cycling and consequently improved battery performance and lifetime.
- Enhanced customer satisfaction.
- Excellent selling feature.

The requirements of a battery state of charge indicator are in many ways similar to those of a fuel gauge for a car. The most important requirement of the indicator is not accuracy per se, but that an easy to read, reliable indication is given to the end user. The possibility of the indicator showing a part full battery when the battery is completely empty must be avoided. A slightly pessimistic display at all times is therefore needed.

2. MEASUREMENT STRATEGIES

In order to give battery state of charge indication, some method is needed to measure the battery state. Two potentially practical solutions exist:

- Absolute voltage measurement.
- Charge measurement.

2.1 Absolute Voltage Measurement

With rechargeable batteries, the variability of the discharge voltage with temperature, age and loading means that state of charge indication using cell voltage is not as simple as it might first appear. With NiCd and NiMH cells, the flatness of the voltage characteristic during a single discharge cycle further complicates use of absolute voltage. Figure 1 illustrates the problem.

2.2 Charge Measurement

Measuring the charge supplied to and withdrawn from the battery pack provides us with a direct gauge of how much energy is left in the battery. The capacity of the battery does not change with temperature, age and discharge rate to the same extent as absolute cell voltage - see Figs 2a and 2b. However for the potential accuracy of the technique to be reached, two areas of design need care:

- Allowance must be made for the charge acceptance ratio of the battery, which will normally be less than unity.

- There must be a phase in the charge-discharge cycle when the pessimistic counter is brought into alignment with the battery state. If this phase does not occur, then the counters intentional pessimism will cause it to become completely out of line with battery state over a few charge-discharge cycles.

With careful design, charge measurement is an accurate and reliable method of measuring the state of charge of rechargeable batteries. This is the method used in SAA1500T.

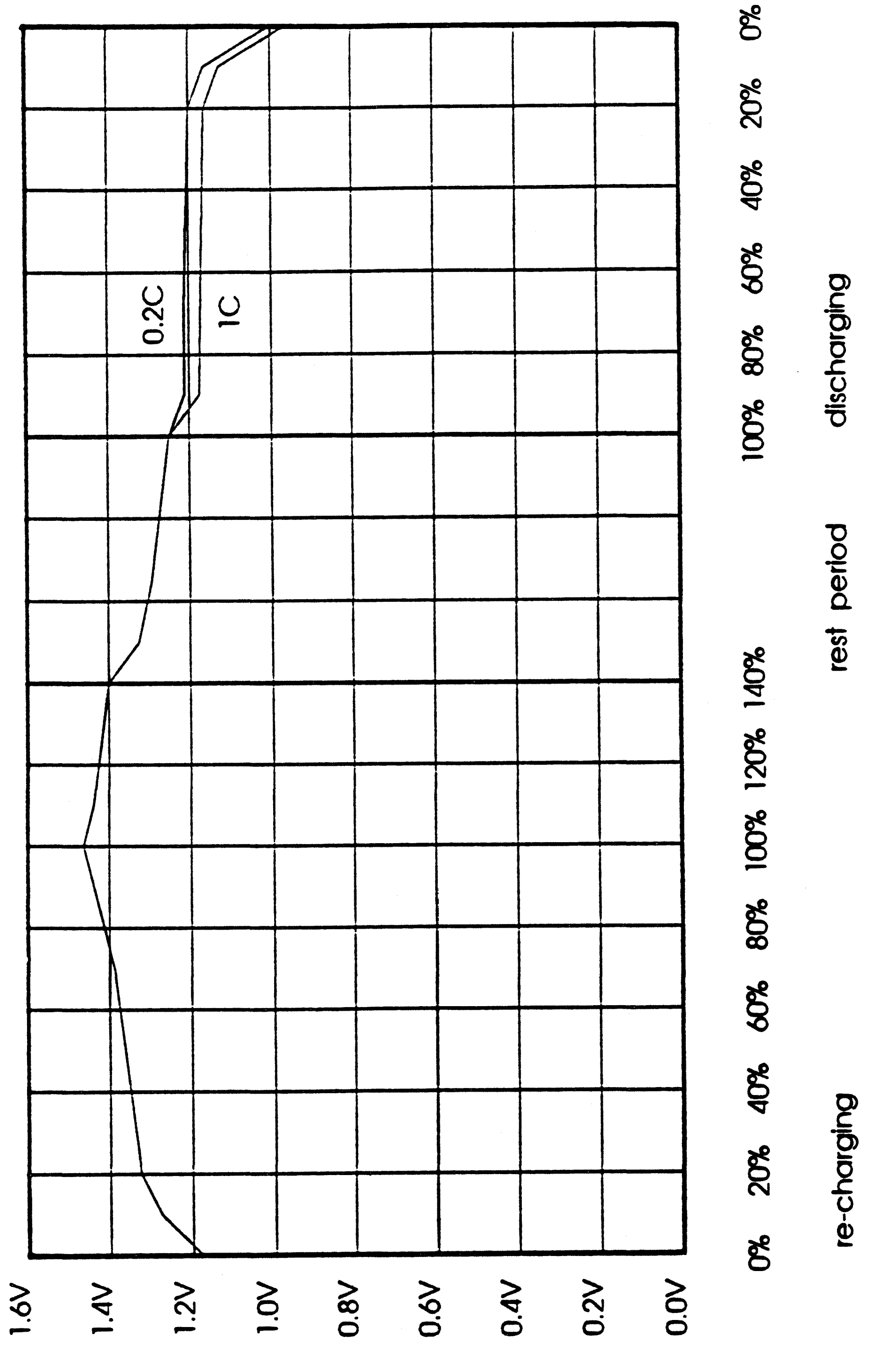

Fig 1 Typical Absolute Voltage of NiCd Cell versus State of Charge

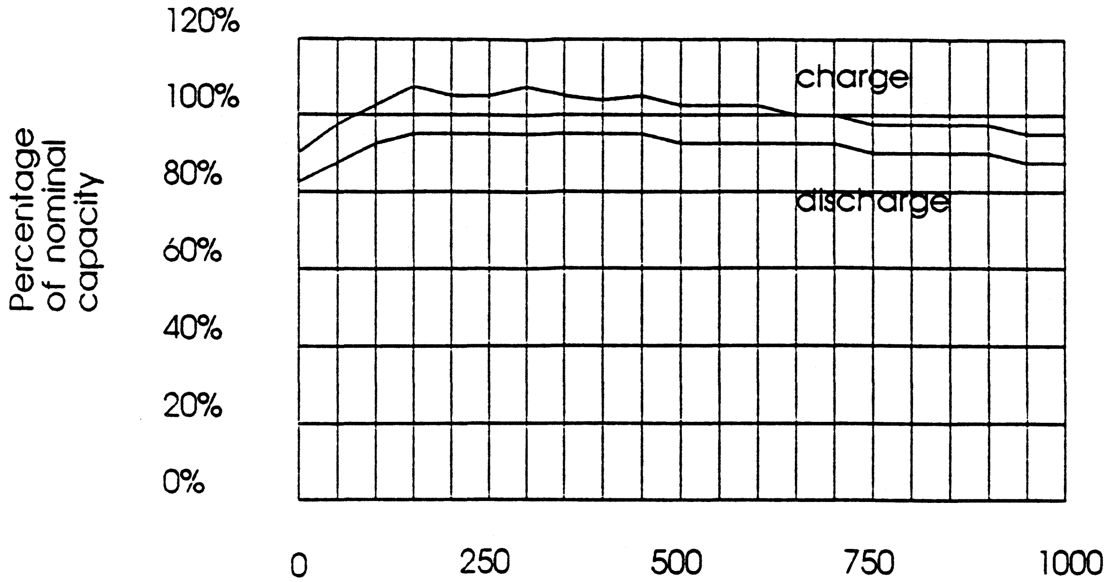

Fig 2a Typical NiCd Battery Charge/Discharge Capacity versus Number of Cycles

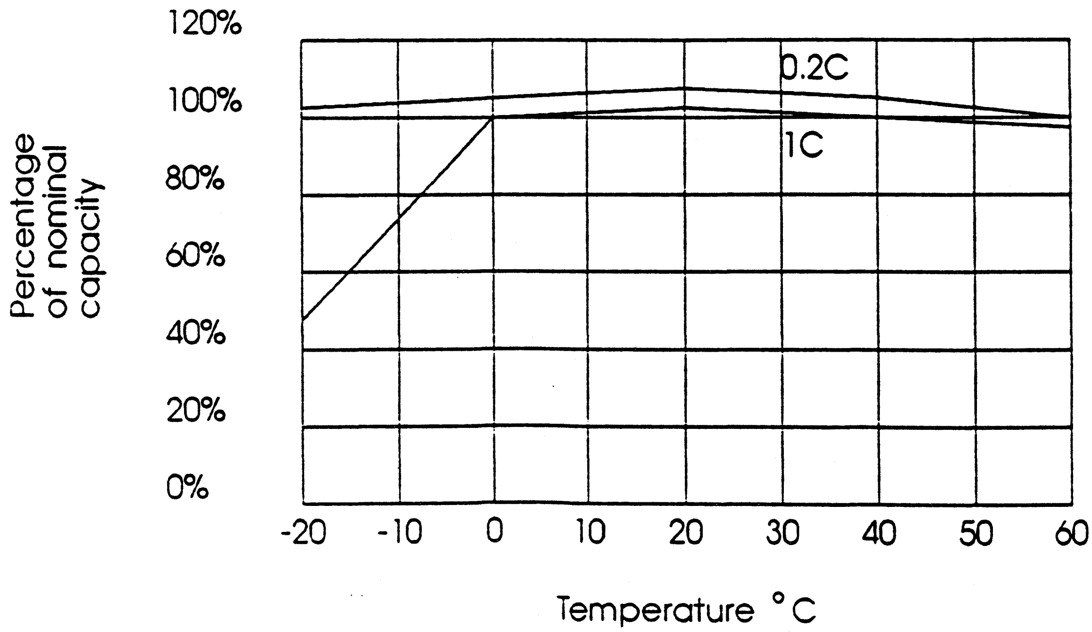

Fig 2b Typical NiCd Battery Discharge Capacity versus Temperature

3. STATE OF CHARGE INDICATOR BASED ON CHARGE COUNTING

The state of charge indicator presented here functions on the basis of counting charge (ampere hours) during discharge, and time during (fixed current) recharging and self-discharge. The circuit can be built using surface mount components to form a compact assembly permanently integrated into the battery pack.

3.1 Recharging

For the circuit design of Fig 9, the battery pack must be dedicated to a particular battery charger of known recharge current and hence recharge time. If the charge current is not known, then it is possible to vary the count rate during recharging proportionate to current using the additional circuitry shown in Appendix A.

When recharging, the rate at which the standard circuit of Fig 9 counts up corresponds to the maximum recharging time. So at the end of recharging, a short phase occurs where the battery is full, (which the battery charger may or may not detect), and the indicator shows that the battery is only partly full. In this phase the battery charger must be left connected, and the indicator allowed to continue to count up to 100%. This makes sure that when the indicator displays 100%, the battery is indeed full. This does not result in overcharging however, since the battery charger retains control over the amount of charge supplied to the battery.

Note: If the battery charger goes into a pulsed trickle charge mode, then the fixed oscillator of the SAA1500T will speed up to the rate used in self-discharge mode. This shortens the final phase of recharging where the counter is catching up with the battery state. However if pulsed trickle charge takes place for some reason other than battery full (eg: faulty battery or over-temperature), then an incorrect count will occur.

3.2 Discharge

So that an accurate gauge of battery state is kept while a variable discharge current is drawn, the count rate during discharge is made proportionate to discharge current. This is important in a number (the majority) of applications where the load placed on the battery is not constant.

The discharge counter is set up to count the number of ampere-hours which correspond with the minimum capacity of the battery. In this way, the display is never caught out by showing for example 20% full when the battery is in fact completely empty.

3.3 Self-discharge

When the battery is neither being recharged or discharged, the counter counts down at a slow rate to allow for self-discharge of the battery. This count rate is typically set for a complete discharge time of between 50 and 200 days. This feature again ensures that the indicator does not overestimate the energy left in the battery.

4. SAA1500T FUNCTIONAL DESCRIPTION

The SAA1500T is a SACMOS integrated circuit designed to provide state of charge indication for rechargeable batteries. A block diagram of the IC is shown in Fig 3, pin functions in Table 1 and electrical characteristics in Appendix A.

SAA1500T Features:

- Five segment LED or six segment LCD display of state of charge.
- LED and audio output for battery empty warning.
- LED indication of recharging.
- Discharge countdown rate proportionate to discharge current.
- Recharging, discharge and self-discharge counted to ensure accurate display.
- Output signal to control battery charger.
- Counter reset on battery connection.
- Low quiescent current (90 µA maximum) maximizes battery life.
- SO20L (SOT163.7) package.

4.1 Display Function

The SAA1500T is intended to display state of charge of the batteries in a six segment LCD bar graph or five segment LED display. Further LED indication is given for batteries nearly empty, batteries on recharge and batteries full during recharging. Outputs L100, L80, L60, L40, L20 and FULL are designed to drive a LCD bargraph with output BP connected to the backplane of the LCD. If however BP is connected to ground (Vss) then outputs L100, L80, L60, L40, L20 may directly drive LEDs with their anodes connected to the positive supply (Vcc). Outputs MO and R1 are able to drive LEDs directly, with MO indicating batteries on recharge (LED constantly lit) and batteries full while recharging (LED flashes), and R1 indicating that the battery is nearly empty. Output R2 provides a second battery nearly empty signal which can be used to drive a simple electroacoustic transducer with a 2 kHz audio tone via an external transistor. Circuit is shown in Appendix A, Fig 10.

Figures 4 and 5 chart operation of the display in recharge, discharge and self-discharge mode, and during switch-over between the modes. Figure 6 shows the signals available from outputs R1 and R2.

4.2 Counter Modes

The circuit counts cycles of a switched variable/fixed frequency oscillator in a counter which can have six user and two test modes. The mode selected is determined by the signal applied to inputs SN and PN. The SN input responds to the load state:

With the load switched OFF: SN = 1

With the load switched ON: SN = 0

The PN input responds to four different signals related solely to any external power source connected to the battery:

PN = 0 is a test mode

PN = 1 for no external power source

PN less than 14 kHz with a 'low current' supply, and PN greater than 20 kHz for a 'high current' supply.

The low and high current options can be used in special cases where for example either a mains or automotive supply is available. Usually the distinction can be ignored however, and the high current option alone used.

Combination of the two signals PN and SN produces the eight modes as shown in Table 2.

4.3 Enable Output

If the battery pack and the battery charger are contained in a single box, then it is possible to use the EN output to decide when to stop charging the batteries. When used with a LED bargraph the EN signal is high when the indicator shows not full, and provides a pulsating trickle charge waveform with 5% duty factor of ten second period when the indicator shows full. If a LCD bargraph is used, then when the indicator shows full, the EN output goes into a continuous high impedance state. See Fig 7.

4.4 Power on Reset

The Power On Reset (POR) pin responds to connection of the batteries and performs a counter reset when the POR pin is in the range of 0 to 1.8 V.

Table 1 IC Pinning

Pin No	Name	Description
1	EN	enable, controls the battery charger.
2	PN	recharge power OFF detection.
3	POR	batteries connected reset, resets counter.
4	Vcc	positive supply.
5	Ct	oscillator capacitor.
6	Ro	resistor for fixed oscillator.
7	Rc	resistor for variable oscillator.
8	Ci	current sense input (discharge).
9	SN	load switched OFF detection.
10	MO	recharge indicator.
11	R2	empty cell warning - buzzer.
12	Vss	negative supply.
13	Full	full indication after 100% charge, LCD only.
14	L100	100% charge indication, LCD and LED.
15	L80	80% charge indication, LCD and LED.
16	L60	60% charge indication, LCD and LED.

contd:

Pin No	Name	Description
17	L40	40% charge indication, LCD and LED.
18	L20	20% charge indication, LCD and LED.
19	BP	LCD backplane, LED detection (connected to Vss).
20	R1	empty cell warning - LED.

Table 2 SAA1500T Operation Modes

SAA1500T Operation Modes			
State of Inputs PN	SN	Operation Mode	Number of Oscillator Cycles for Full Count
0	0	Test, countdown fast.	5.12×10^3
<14 kHz	0	Low current supply, discharge, countdown.	8.85×10^6
>20 kHz	0	High current supply, no count.	---
1	0	No supply, discharge, countdown	8.85×10^6
0	1	Test, count up fast.	5.12×10^3
<14 kHz	1	Low current supply, recharge, count up slow.	2.36×10^8
>20 kHz	1	High current supply, recharge, count up.	7.37×10^6
1	1	Self discharge count down slow.	7.08×10^{10}
1	1	Self discharge count down slow.	3.54×10^{10} see note

Note: Self discharge counts at double normal rate for first battery discharge cycle.

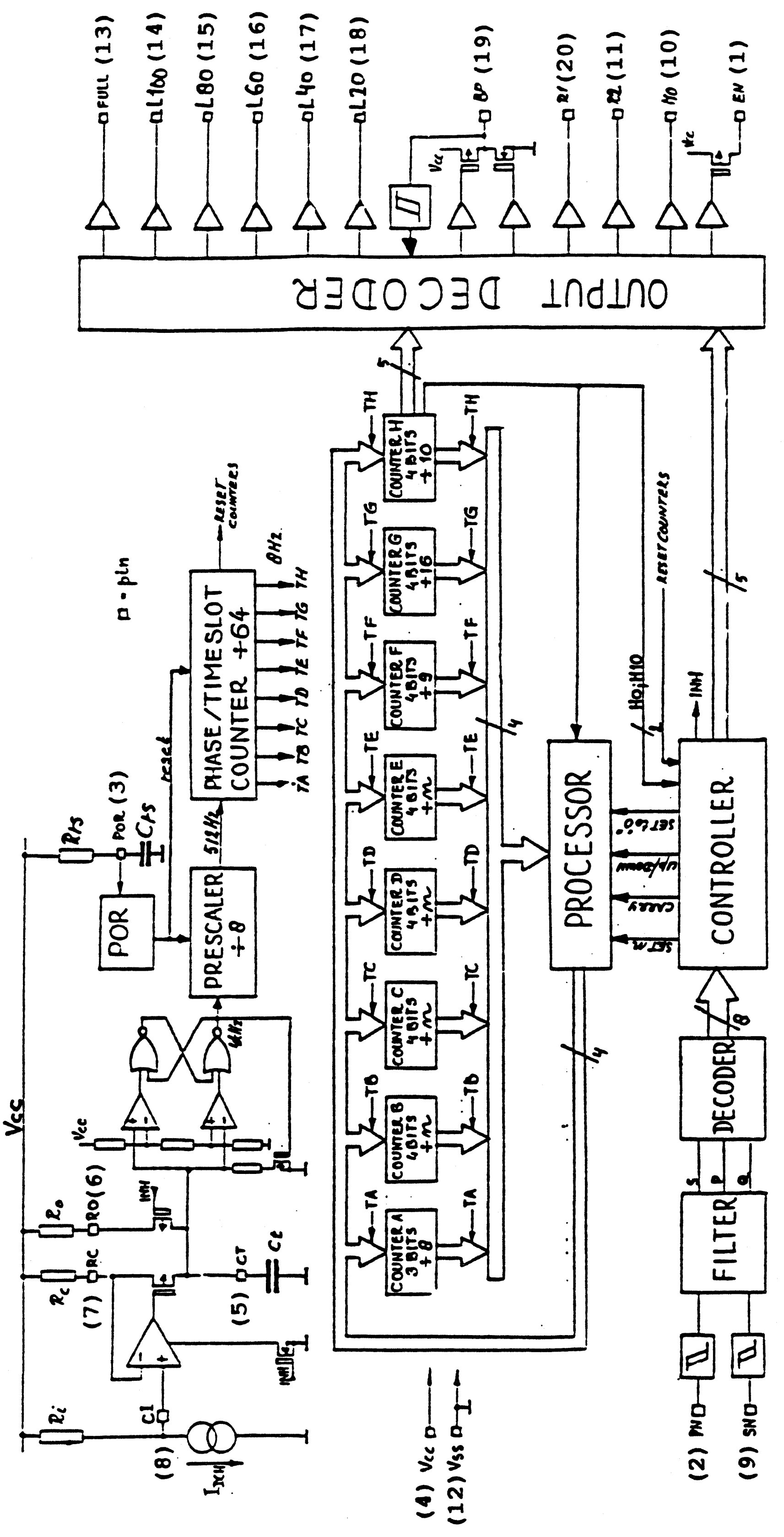

Fig 3 SAA1500T Block Diagram

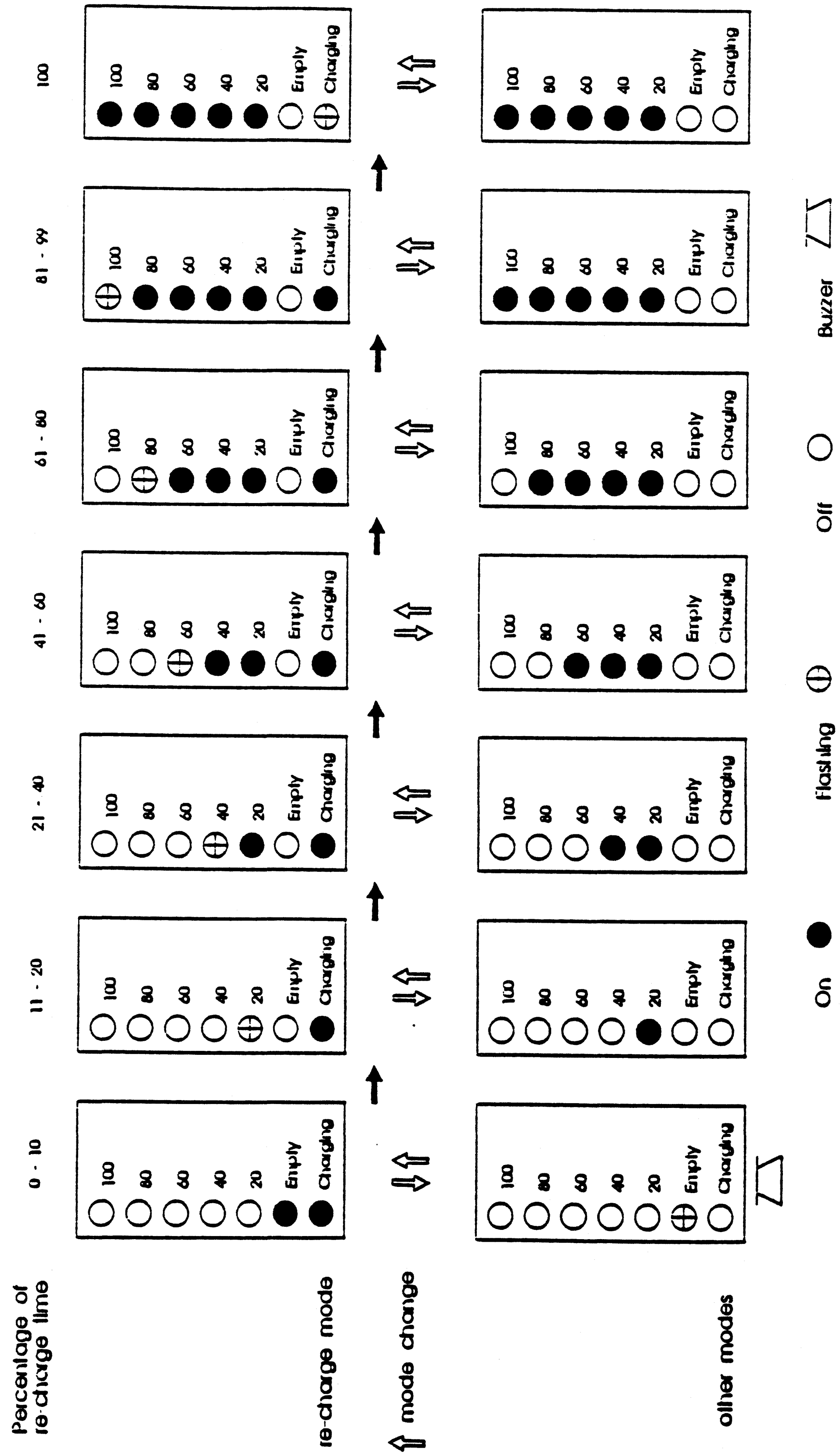

Fig 4 LED Display During Recharging

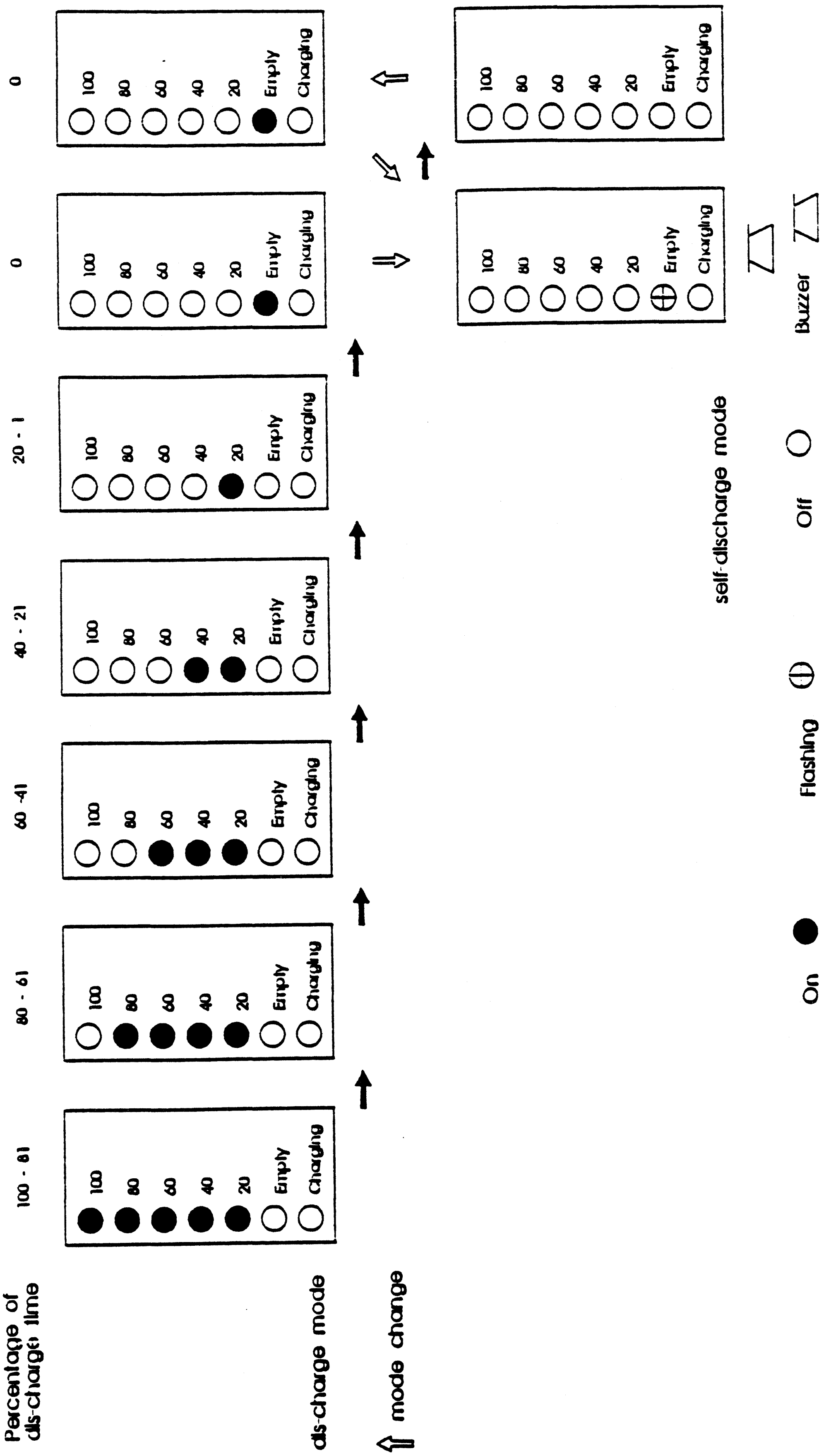

Fig 5 LED Display During Discharging

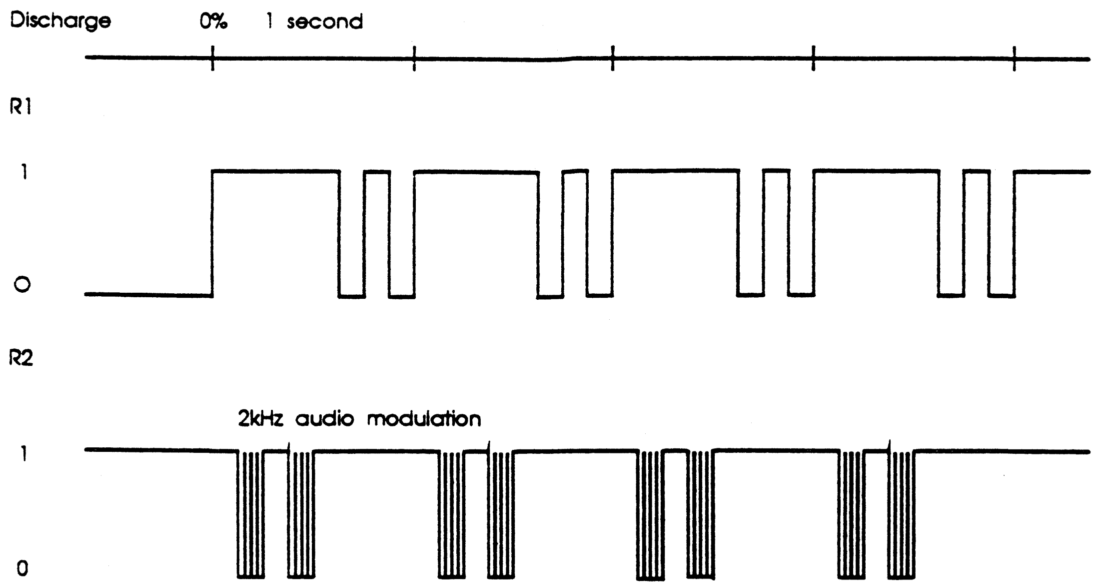

Fig 6 Waveforms of R1 and R2 Signalling Batteries Empty

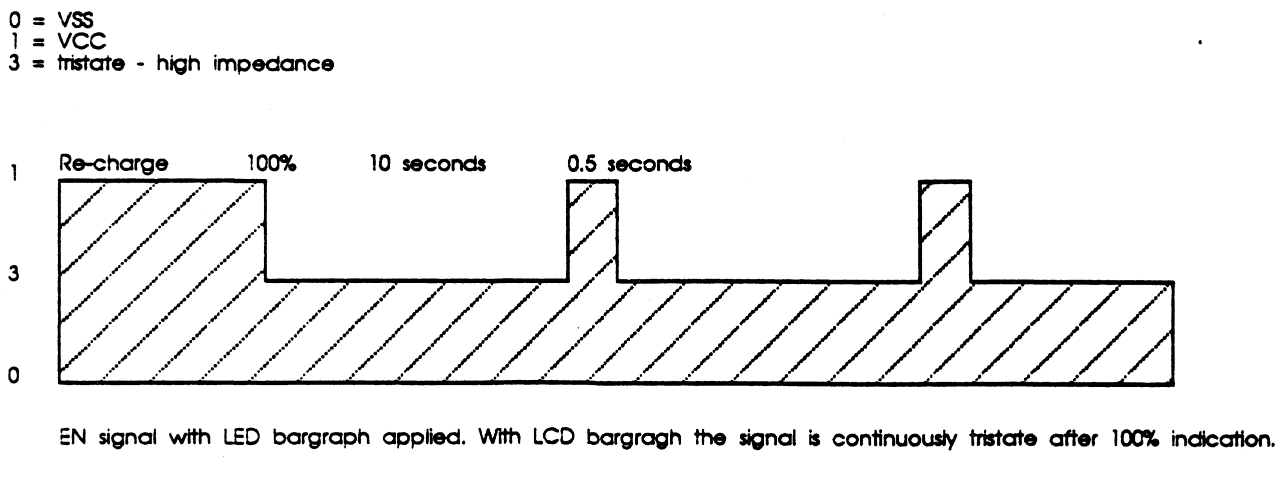

Fig 7 Waveform of EN Signal with Full Batteries

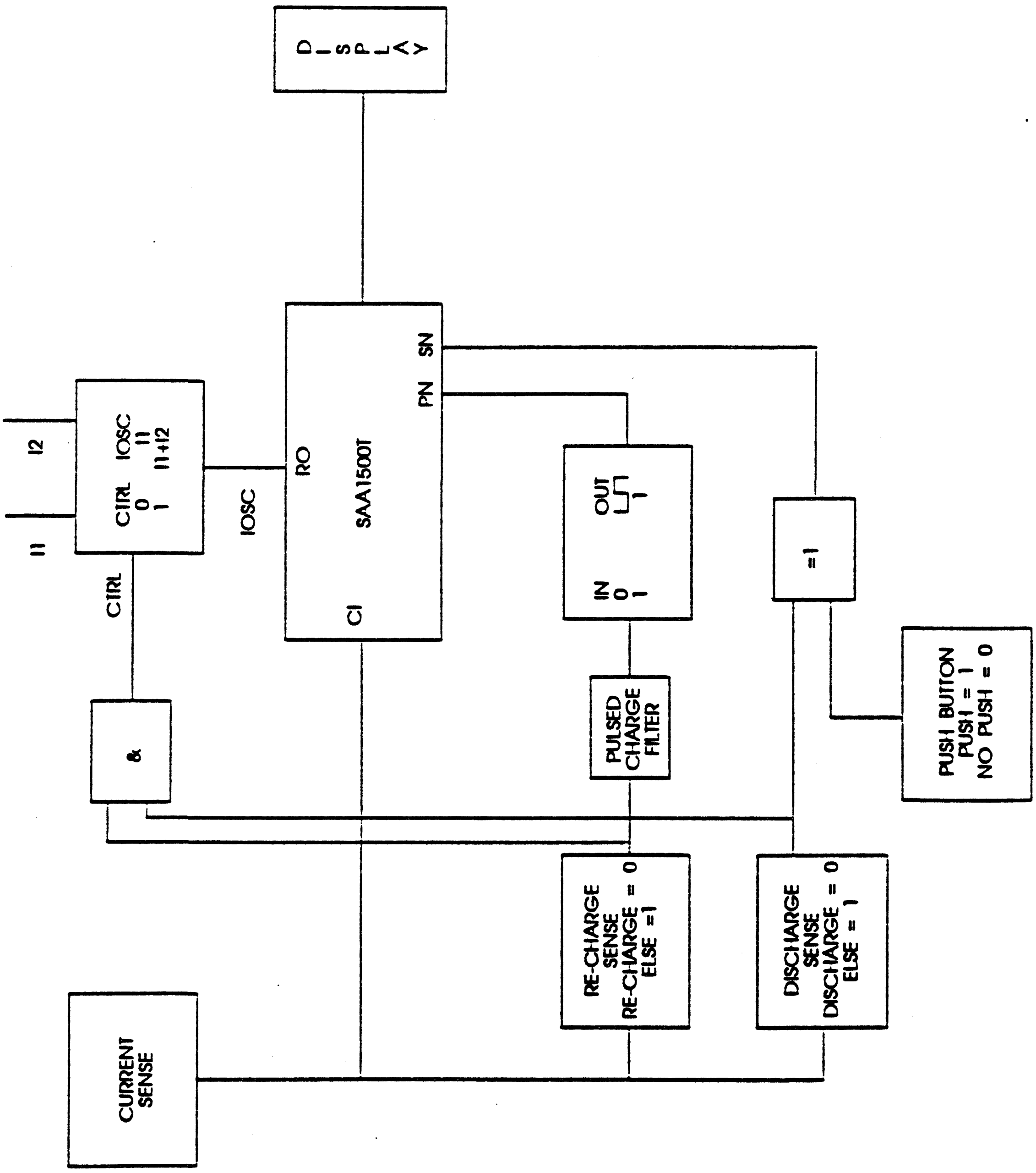

Fig 8 State Of Charge Indicator Block Diagram

5. CIRCUIT DESCRIPTION

In order to use SAA1500T as part of a battery pack with the usual two terminals, the counter control signals SN and PN must be generated inside the battery to ensure that the charge count progresses at the correct rate in the correct direction. The circuit block diagram of Fig 8 outlines how this is achieved. Figure 9 shows the complete schematic diagram.

5.1 Mode Determination

Only three of the possible eight modes are required; recharge, discharge, and self-discharge. To detect which of these modes is required, a bidirectional current sense circuit based on two op-amps is used. From the two op-amps emerge two signals which correspond to equipment not in use, and battery not being recharged. From these two lines the SN and PN signals are derived. The recharge line is buffered in such a way that pulsating trickle charge is counted in the same way as continuous charge current, but with the oscillator running at an increased rate.

5.2 Second Fixed Oscillator Frequency

To allow for a wide range of self-discharge times, a diode switch is used to control the resistance seen on the fixed oscillator input, giving two discrete frequencies of fixed oscillator. This is necessary since the numerical count for both recharge and self-discharge is fixed, and therefore the only way to vary self-discharge and fast charge time independently is to alter the fixed oscillator frequency.

5.3 Display Operation

To produce a display at the push of a button, the SN line is toggled. The user has to hold the button until a display is given (less than one second), and then release. Use of the button is not necessary during charging when the display is permanently lit. Additionally the nearly empty indicator comes on at appropriate times as a warning signal.

5.4 Supply Reduction

In order to keep within the specified operating supply range of the SAA1500T (2.0 V to 4.0 V), and yet keep at least 3.0 V applied to the peripheral circuitry, voltage regulation is required. Transistors V1 to V5 perform this function with minimal voltage drop or current drain.

6. STATE OF CHARGE INDICATOR PERFORMANCE CHARACTERISTICS

State of Charge Indicator Performance Characteristics	Min	Max
Battery voltage range.	3.0	18.0 (V)
Linear range of discharge current.	0.3	5 (C)
Quiescent current consumption.	---	600 (μA)

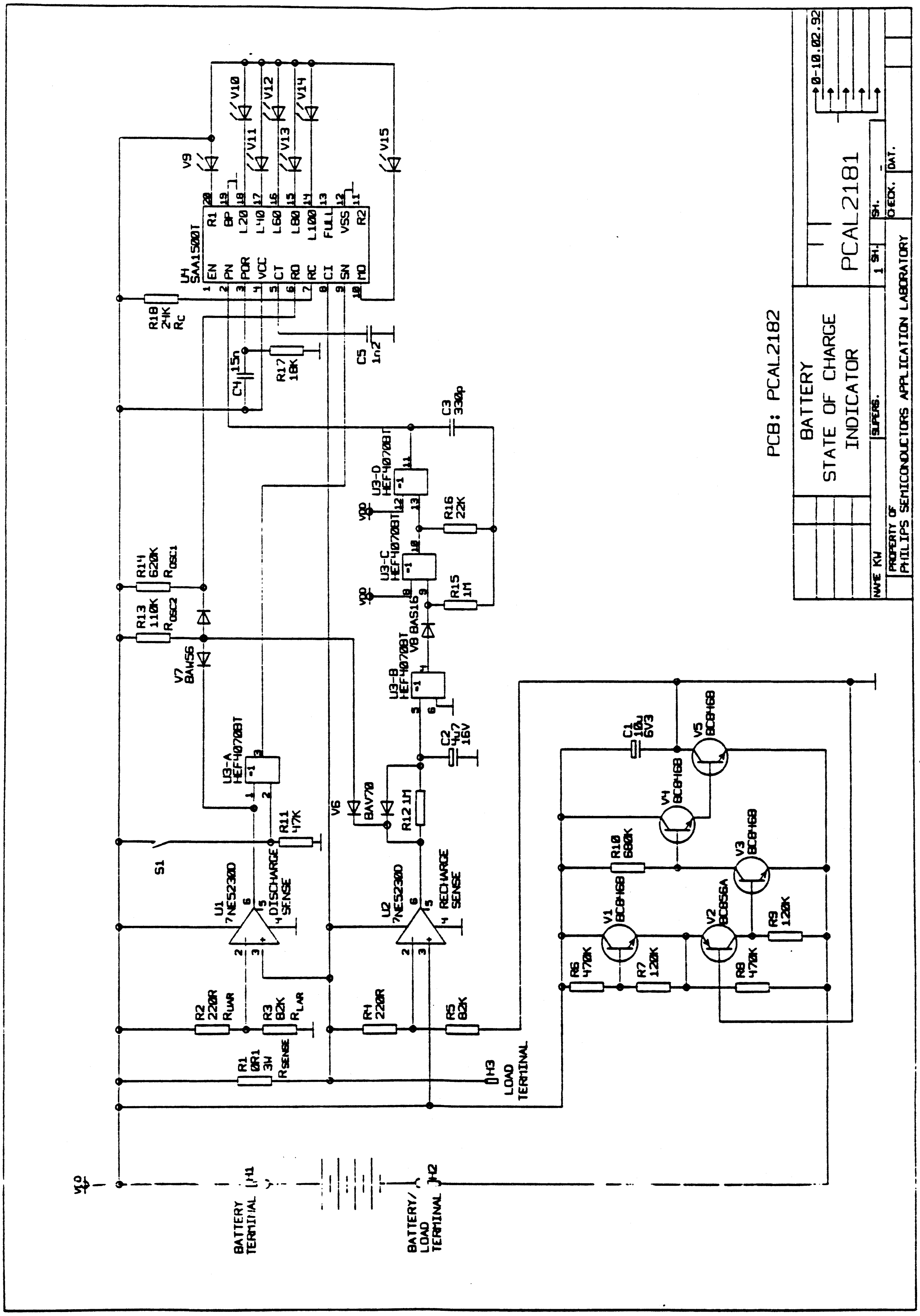

Fig 9 Battery State Of Charge Indicator Circuit Diagram

7. COMPONENT SELECTION

Selection of components and component values for various battery capacities, recharge time and self-discharge rate.

7.1 Op-Amp/Comparator Selection

The op-amps used as current detectors in this application have to work under rather awkward conditions.

- Input common mode range to include positive supply of op-amp.
- Very low quiescent current allowed (op-amps powered continuously).
- Low supply voltage.
- Logic compatible output.
- Input offset small to allow small current sense resistor and sensing of small currents.

The NE5230 is a suitable device for the system described in this report, however final selection will depend on the application.

7.2 Rsense

The value of Rsense is a compromise between a number of factors. A small value reduces power dissipation, minimises voltage drop, and retains the characteristically low impedance of NiCd batteries. Thus a low value is highly desirable. However too low a value causes a problem: Low recharge or discharge currents produce only a very small sensed voltage. This increases the cost of op-amp required to detect a given minimum current, (low offset voltage requirement) and potentially makes layout more critical.

The best value for Rsense then is the minimum consistent with being able to detect the minimum required current using the chosen op-amp.

7.3 Minimum Current Sense Setting Resistors

The two resistors Ruar (upper arm resistor) and Rlar (lower arm resistor) associated with each op-amp in the current sense circuit, set the minimum current that can be sensed in recharge (op-amp A1) and discharge (op-amp A2). When choosing these resistors the op-amps maximum offset voltage must be considered along with the minimum supply voltage and the minimum current that is required to be sensed.

The minimum sensed current Imin is:

$$Imin = \frac{Ruar\,Vsup}{(Ruar + Rlar)\ Rsense} \pm \frac{Vos}{Rsense}$$

Where Vos is the maximum op-amp offset.

Obviously the offset term must be less than the first term, or the circuit will behave very erratically!

7.4 Setting the Oscillator Frequency During Recharge - Roscl

Resistor Roscl determines the fixed oscillator frequency during recharging. This frequency should be set to give the maximum charge time that is possible with a given battery charger. Where the maximum charge time is not known, it can be calculated from the charge current as:

$$\frac{1.5 \times 60 \times Battery\ Capacity\quad (Ah)}{Battery\ Charger\ Output\ Current\ \ (A)} \qquad (minutes)$$

$$Eqt\,1 \qquad (required)\ foscl\ (Hz) = \frac{122834}{Maximum\ Charge\ Time\ \ (minutes)}$$

$$Eqt\,2 \qquad Roscl = \frac{\left[\frac{1}{Foscl} - 17\ \mu s\right]}{0.7 \times Ct} \qquad (approximate\ equation)$$

7.5 Setting the Oscillator Frequency During Self-Discharge - Rosc2

Resistor Rosc2 is switched in parallel with Rosc1 to give an increased oscillator frequency during self-discharge mode. This is necessary when use of the fosc1 frequency would make the self-discharge time too slow.

$$Eqt\,3 \qquad (Required)\ Fosc2\ (Hz) = \frac{819444}{Self-discharge\ time\ Min\ (days)}$$

$$Eqt\,4 \qquad Rosc2 = \left[\frac{0.9 \times Ct}{\frac{1}{Fosc2} - 17\ \mu s} - \frac{1}{Rosc1} \right]^{-1}$$

approximate.

7.6 Setting the Discharge Count Down Rate - Rc

Resistor Rc determines the count rate during discharge.

$$(Required) \quad Fosc3 = \frac{3440 \times Idschg}{Ah\ capacity}$$

$$(In\ circuit) \quad Fosc3 = \frac{2.85\ Rsense \times Idschg}{Rc \times Vcc \times Ct}$$

Therefore:

$$Eqt\,5 \qquad Rc = \frac{Rsense \times Ah\ capacity}{1207 \times Vcc \times Ct}$$

8. DESIGN EXAMPLE - APPLICATION TO A 9.6 V 1500 mAh CAMCORDER BATTERY

Specification:

Battery:	Minimum capacity. Voltage. Self discharge time.	1300 mAh 9.6 V 100 days
Camcorder:	Maximum current in use. Minimum current in use. Minimum operating voltage.	3.0 A 150 mA 6.0 V
Battery Charger:	Recharge current. Maximum charge time.	2.25 A 60 mins

Step 1 Choose Rsense value

The minimum Rsense value is determined by the input voltage offset of the chosen op-amp, and the minimum current which must be sensed. If we choose NE5230 op-amps, then we have to accomodate a maximum offset voltage of 4 mV. Therefore, to sense the minimum charge current of 150 mA, the minimum possible Rsense value is:

$$\frac{2 \times 4\,mV}{150\,mA} = 54\,m\Omega$$

a value of 100 mΩ is chosen for a practical circuit to provide a further margin of safety.

Step 2 Calculate Rlar and Ruar.

To be able to sense a minimum of 150 mA, the nominal voltage reference at the op-amp input must be (allowing for offset voltage ± 4 mV and Rsense tolerance ± 10%):

$$150\,mA \times 90\,m\Omega - 4\,mV = 9.5\,mV$$

Which with a supply rail of 3.5 V requires a divider ratio of:

$$\frac{3.5\ V}{9.5\ mV} = 368$$

Thus resistor values for Ruar and Rlar of 220 Ω and 82 kΩ are appropriate. Keeping these values high reduces power consumption, but care needs to be taken with the op-amp input bias current.

Step 3 Determine Fosc1, Rosc1 (used in recharge)

Use Eqt 1 $$Fosc1 = \frac{122834}{60} = 2048\,Hz$$

Use Eqt 2 $$with\ Ct = 1n2$$

$$Rosc1 = \frac{\frac{1}{2048} - 17\ \mu s}{0.7 \times 1n2} = 561\ k\Omega$$

Which, choosing the next highest (conservatively slow charge rate) resistor value becomes 620 kΩ.

Step 4 Determine Fosc2, Rosc2 (used in self-discharge)

Use Eqt 3 $$Fosc2 = \frac{819444}{100} = 8195\,Hz$$

Use Eqt 4 $$Rosc2 = \left[\frac{0.9 \times 1n2}{\frac{1}{8195} - 17\ \mu s} - \frac{1}{620\ k} \right]^{-1} = 115k3$$

Which choosing the next lowest resistor value (conservatively fast self-discharge time) becomes 110 k.

Step 5 Determine Rc (used in discharge).

$$Use\,Eqt\,5 \qquad Rc = \frac{0.1\,\Omega \times 1.3\,Ah}{1207 \times 3.5\,V \times 1n2} = 25k6$$

Which choosing the next smallest value (conservatively fast discharge time) becomes 24 kΩ.

All values are now determined, but since the oscillator equations are not exact, should be verified in circuit.

9. APPLICATIONS

The state of charge indicator presented here is designed to be part of a stand alone battery pack as used in Camcorders. However, the design is equally suited to a wide range of applications such as Laptop Computers, Personal Audio and Portable Tools, provided the SAA1500T is permanently connected to the battery pack. It should also be noted that in order to guarantee correct operation, only fully discharged batteries should be installed in the equipment.

APPENDIX A

Circuit Options

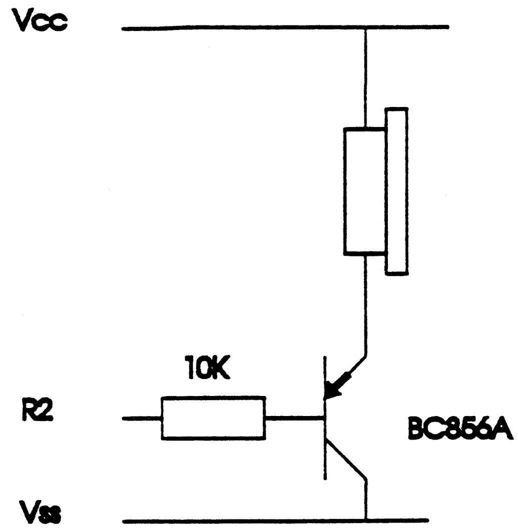

Fig 10 Audible Warning Output

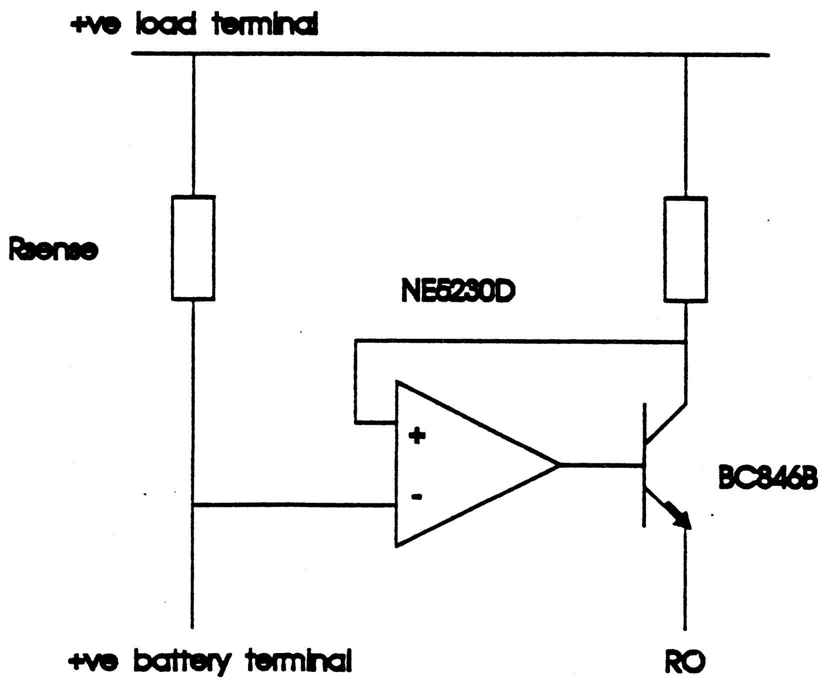

Fig 11 Recharge Current Measurement Circuit

APPENDIX B

SAA1500T Operating Characteristics

	Min	Max	Unit	Vcc	Condition
Operating voltage.	2.0	4.0	V		
Operating ambient temperature.	0	70	°C		
Output voltage HIGH outputs: BP, FULL.	2.0		V	2.4	Io = 650 µA
Output voltage HIGH outputs: R2, EN.	2.0		V	2.4	Io = 1 mA
Output voltage HIGH outputs: MO, R1, L20, L40, L60, L80, L100.	2.0		V	2.4	Io = 300 µA
Output voltage LOW outputs: BP, FULL.		0.4	V	2.4	Io = 650 µA
Output voltage HIGH outputs: R2, EN.		0.4	V	2.4	Io = 1 mA
Output voltage LOW outputs: MO, R1, L20, L40, L60, L80, L100.		0.55	V	2.4	Io = 5 mA
Schmitt trigger HIGH inputs: PN, SN, BP.	1.6 3.2		V V	2.0 4.0	
Schmitt trigger LOW inputs: PN, SN, BP.		0.4 0.8	V V	2.0 4.0	
Input voltage HIGH input POR.		1.55	V	1.8	
Input voltage LOW input: POR.	0.75		V	1.8	
Input current input: CT.	150	360	µA	2.4	VCT = 2.4 V
Supply current.		90	µA	2.6	VPOR = 0 VCI = 0 VCT = 0 VRC = 0

Absolute maximum storage temperature range: -65 to +150 °C.

Package: S020L (SOT163.7).