

# CHARGE

## alkaline cells



**If you try to charge an alkaline cell using any of the traditional methods - it will explode, causing a potentially serious health hazard. But, as Rod Cooper shows here, there is a recipe to recharge them safely - resulting in substantial cost savings if you rely heavily on alkaline cells.**

It has been known for a long time that the manganese dioxide/zinc couple is rechargeable. Even before World War II zinc-carbon cells were being given recharging treatment by some of the larger commercial users like cinemas but the techniques used were crude.

In 1953, R W Hallows wrote an article for *Wireless World* with an analysis of these simple methods. He followed this up in 1955 with a review of a device from Holland called the Electrophoor which recharged zinc-carbon cells using a principle called periodic current reversal.

Briefly, this system entailed the use of a continuous train of pulses to charge the cell - a method which had been tried before without much success. But in this case each large forward pulse of current which charged the cell was followed by a smaller pulse discharging it.

The combined result was to charge the cell in a series of steps, two steps forward, one step back. It may seem strange to apply what is in effect an ac charge to a decidedly dc device like a cell, but it works.

Periodic current reversal, or pcr, was already in use by the electroplating industry to prevent the formation of metal dendrites and to give smooth, hard, compact metal deposits. When used to recharge zinc-carbon cells, it had a similar effect on zinc. The main difference between plating and charging was that cell chargers tended to use the mains frequency for pulsing. Hallows pointed out that dendrite formation was one of the main reasons for failure in recharging the zinc-carbon cells. When using dc, pulsed or not, zinc dendrites would quickly form across the separator and short-

circuit the cell internally. Periodic current reversal prevented that to a large extent.

Following the Electrophoor, which was a very simple device and easily copied, several other chargers appeared on the market, and to counter their popularity the battery manufacturers started a campaign to convince the public that recharging zinc-carbon cells was unsafe. This was demonstrably untrue. In the mid-seventies there was a well-publicised success by the pro-charging lobby in the Japanese courts to stop this propaganda. This success was not repeated in the United Kingdom or the rest of Europe.

However, these chargers were soon overtaken by events as the popularity of the zinc-carbon cell was already falling - even though a design with an improved format - the zinc chloride type, had appeared. The alkaline-manganese cell, as typified by Duracell, was taking over and these simple chargers could not recharge the new cell. If it was attempted, the cell split and spewed caustic electrolyte everywhere - sometimes explosively.

In the brief period 1981 to 1985, the share of the market taken by alkaline cells increased from 24.5% to 42.6% a process that has continued - though perhaps less dramatically - to this day. The size of the market for alkaline-manganese cell just in the UK was then £230million - so what must the world-wide figures be now?

Rechargeable cells using NiCd have appeared since then but their progress has been dogged by technical shortcomings (see *Wireless World* Jun-Sep '85 'Failure modes in NiCd cells) and they have taken a compara-

### Warning

**You must not attempt to replicate Rod's charger design unless you understand the concepts discussed in this article in their minutest details - i.e. you are an experienced electronics design engineer with a good knowledge of cell and battery structures. Any attempt to modify any of the components and/or conditions prescribed for the charger circuit could well result in a health hazard due to explosion or burning.**

tively small part of the total market compared to the alkaline-manganese primary cell.

**Why bother to recharge primary cells?**

The amount spent on alkaline cells represents an enormous quantity of raw materials and engineering energy, and normally all of it goes away after just a brief period of use. This situation has always been seen as a good example of the profligacy of technological business by the environmental lobby – with justification.

The economical and ecological implications of this waste are all too clear. At present there is no recycling to speak of – as there is with glass, paper, and aluminium – despite specific political directives to encourage recovery of the raw materials. Also, these cells are relatively expensive to buy.

In this context, even if a recharging device recycled each cell just once, the saving in raw materials and engineering effort would be enormous. In fact, the P24 design can recharge alkaline cells not just once but several times. The best way to recycle an alkaline cell is obviously not to re-cycle the raw materials but to recharge it.

Because of the continuing claims by battery manufacturers that any sort of recharging of alkaline cells is unsafe, this charger has been given two end-of-charge mechanisms and more than usual effort has been put into testing the safety aspect of the design.

The design below was commissioned for commercial use in 1988 before recharging alkaline manganese cells became generally accepted, so before being submitted commercially it was tested with many hundreds of recharge cycles using cells from many different sources. It has proved itself completely safe but only when used correctly.

**Recharging alkaline-manganese cells**

The 'rules' which shaped this design are listed as follows.

- To be effective, alkaline batteries should be recharged as a single cell, each cell being given its own separate charge regime. Packaged batteries like PP3, PP9 etc. are excluded. Charging these batteries always results in uneven distribution of charge, and leads to reverse charging when discharge takes place. The situation is acute when one cell fails, because this can lead to severe over-charging of the remaining cells in the battery during recharging – which is not safe with alkaline cells – and can result in malfunction of a badly-designed charger. The P24 design charges two cells at a time in

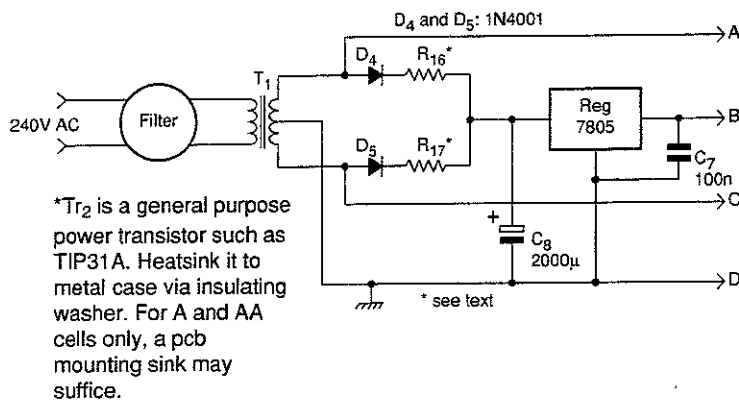
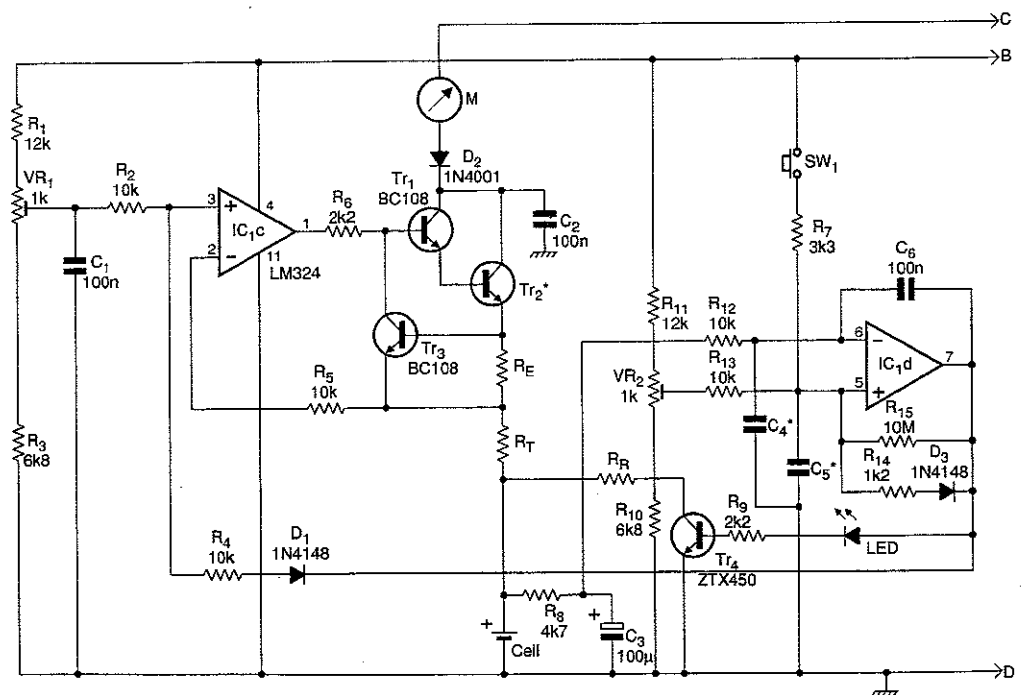
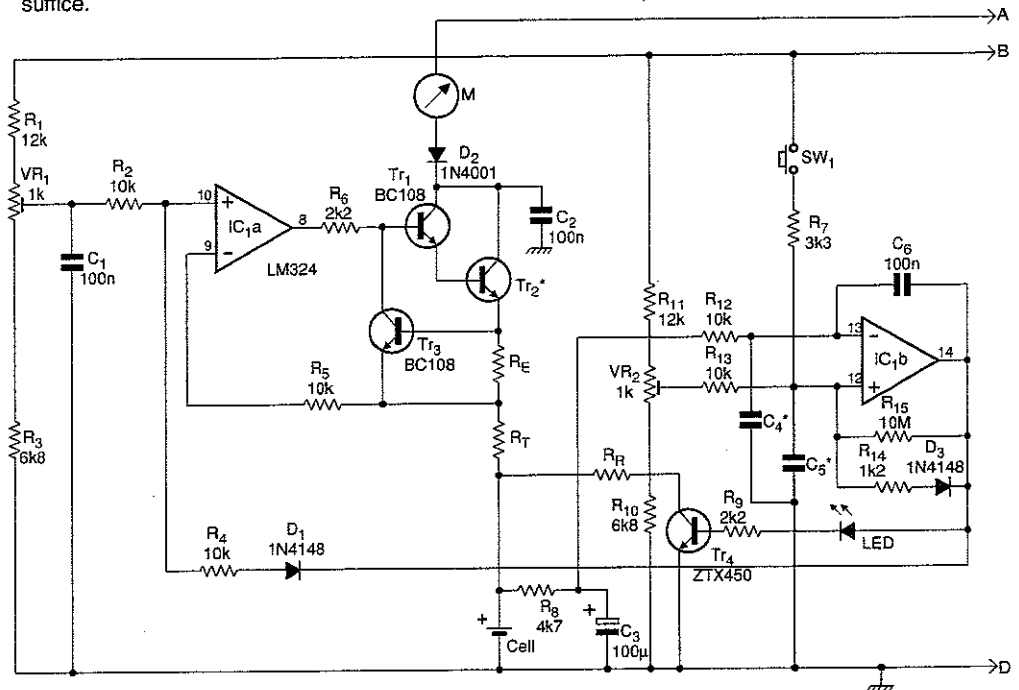


Fig. 1. Complete circuit for charging two alkaline cells. Power supply drives both sections and needs a 6-0-6V transformer rated at 1.5A for D cells, 1A for C cells or 0.5A for AA and below. For the values of R16,17, refer to Ray Fautley's article in the February issue.



## COMPONENTS

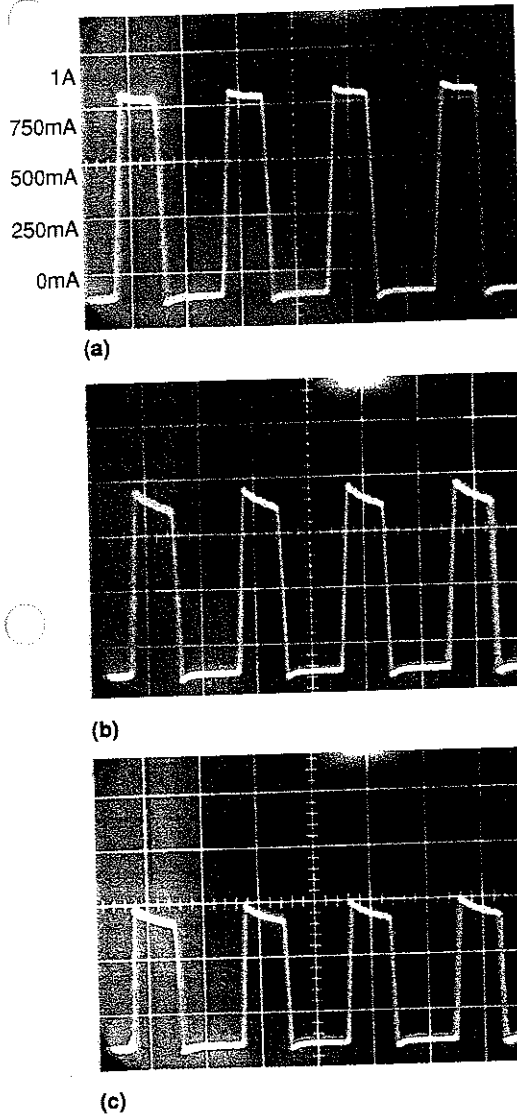


Fig. 2. Oscilloscope views of forward and reverse current in a D cell, a) at start of charge, b) after 1h, c) after 2h, d) after 4h and e) at end of charge, i.e. balance point.

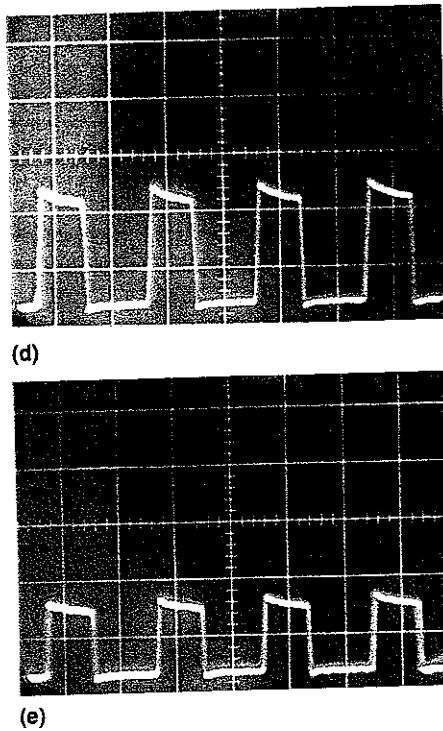


Table 1. Values needed to accommodate the various cell sizes.

	Ah	Rr	Re	Rt
D	15	9.25	0.7	0.3
C	7	20	1.5	0.66
AA	2.25	71	4.9	2.1
AAA	0.8	175	13.5	5.8

separate holders, and treats each cell individually.

- The charging current must be limited to match the charge-acceptance of the cell. One factor affecting the charge-acceptance is the state of charge of the cell. A partly-discharged cell will have a much higher charge-acceptance than a cell approaching the fully charged state – all other things being equal. At full

charge the charge-acceptance of an alkaline cell reduces to nothing, for practical purposes. Because of this characteristic, any charging circuit must adapt to give a charge current appropriate to the state-of-charge. A method called taper charging is commonly used with many batteries, which as the name implies, starts at a controlled large current and dwindles as full charge approaches. This technique is used in modified form in the charger.

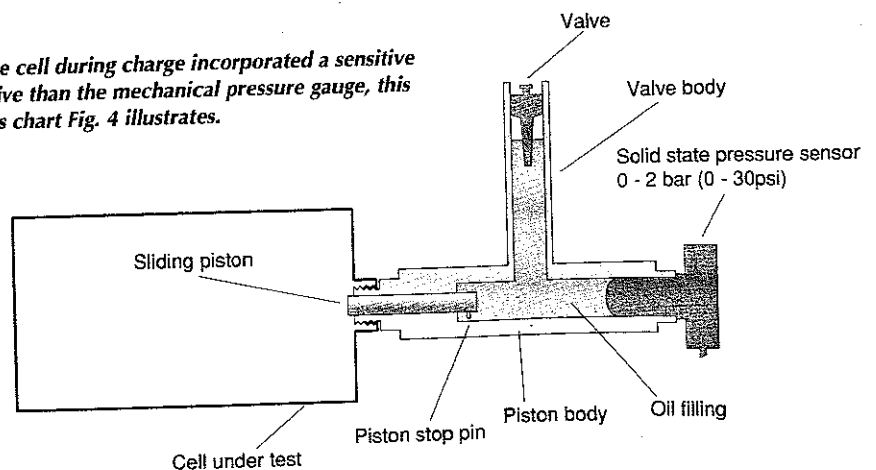
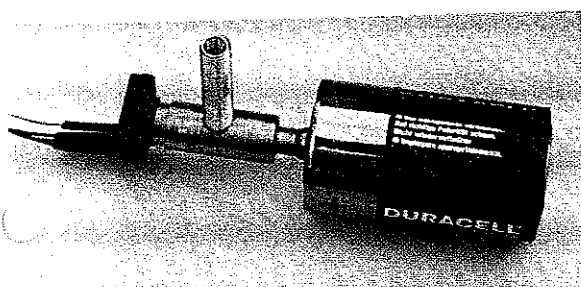
- This design is for use at room temperature. The properties of the alkaline cell vary significantly with temperature. In particular, charge acceptance decreases with falling temperature. Although the commercial version of this design had temperature control, there is no compensation in this version, so a 20°C environment is assumed.

- Current applied to the cell must not exceed a certain maximum charge-acceptance value. For alkaline-manganese cells, this rate is around C/35 to C/40 amps, where C is the capacity of the cell in ampere-hours. There is some variance depending on the origin of the cell. In addition, the charger must be short-circuit proof for safe household use. To deal with both issues, the P24 is made short-circuit proof at the maximum charge acceptance figure. For a D-size cell, the short-circuit current is below 0.5A – safe by any standard.

- Unlike NiCd cells, where overcharge is part of normal operation and is to some extent desirable, no overcharging is permissible with alkaline cells. In the NiCd cell there is a mechanism for recombining the gases produced inside the cell during overcharge, the net result being that the cell merely becomes warm. For the NiCd cell this provides a very convenient overcharge-limiting system. Although a similar mechanism exists for the alkaline-manganese cell, it is not encouraged by the internal structure of the cell, so it cannot be relied on for limiting overcharge. An alkaline-manganese cell could probably be designed with this characteristic but it is unlikely to be produced for obvious reasons. To prevent overcharge, two techniques are used in the P24 charger. First, the charger's taper is made to reduce to nothing well before overcharging can take place. Secondly, a simple voltage cut-out operates at a preset voltage slightly below that produced by the taper. One technique complements the other so that if one method fails the other will back it up. This makes the P24 very safe. In many hundreds of cycles, over eight years, it has never burst a cell.

- The charge method must be the periodic-current-reversal type as discussed above to prevent dendrite formation. In this design, per

Fig. 3. MklI fixture used for monitoring pressure in the cell during charge incorporated a sensitive electronic pressure transducer. Although more sensitive than the mechanical pressure gauge, this version still showed no significant rise in pressure – as chart Fig. 4 illustrates.



is used at mains frequency for the sake of simplicity, but in a modified form as explained later.

● Lastly – but most importantly – for this charging method to be effective, the alkaline-manganese cell must not be discharged below a certain level. Below this level, irreversible chemical changes take place which render the cell progressively less rechargeable. The actual level is a subject of debate, but in the regime I use, I stop discharge after the top 30% of the total cell capacity has been used. For a typical D size cell of 15Ah total capacity, this gives a usable 5Ah to play with. This is about the same as a D-size NiCd cell provides, but without the snags of the NiCd.

### Terminating the recharge cycle

The potential at which gases are evolved from the alkaline-manganese cell is 1.7V at room temperature. Since a voltage slightly less than 1.7V still produces a fully-charged cell, the P24 charger is designed to taper the current to

### Deciding when to recharge

In practice, imposing a 30% limit does not reduce the usefulness of the method as much as you might think. For example, a typical portable radio running on alkaline manganese C cells can run for 24 hours before needing a recharge, and a flash-lamp with two D cells for about 5 hours.

Moreover, in real life, it seems no more trouble to recharge alkaline-manganese cells than it does when using NiCd. Of course, in contrast to NiCd cells, you can use up the whole of the remaining reserve capacity of an alkaline cell at any time if you wish. This is a big advantage.

A problem arises in deciding when the 30% limit has been reached. With a NiCd cell, it is clear enough when the cell needs a recharge, but the 30% limit is more obscure with alkaline cells. Misunderstanding of the 30% limitation and lack of a method of determining the recharge point has resulted in assessments of this method of recharging, such as the *Which?* magazine survey, giving a negative verdict.

For good results, the current taken by the appliance must be known. Once you know this, you can either judge roughly when the cell needs a recharge from knowing the original Ah capacity, in which case you must put up with the effects of any misjudgement, or you can attach simple integrating timer. This could flash a light-emitting diode or operate a cut-out after C/3 Ah has been reached. A low-current timer design will be shown in a subsequent article.

zero at about 1.68V. The cut out operates at 1.62V.

I should mention here in case anyone is tempted to experiment, that this design was not arrived at in a single step. Many circuits were tried in order to provide the 1.68V ceiling – including constant-voltage transformers, electronically stabilised ac supplies, feedback-controlled switch-mode psu and many others. Eventually the circuit of Fig. 1 was arrived at.

### Pulse-balancing

In this technique, instead of charging the cell with a constant ratio of forward to reverse currents, the large forward pulse of the per charge is varied and the small reverse charge is kept constant. This gives the taper charge and can be arranged to give a natural balance at the end-of-charge point.

When the cell is in a partly discharged state, i.e. high charge-acceptance, the forward pulse is large but kept within limits by the current limiting circuit. The limit was set at about C/35 amps, but any setting from C/30 to C/40 provides good recharging.

Various criteria were used to fix the maximum limit; the length of charging had to be practical for everyday use; the cell had to show no signs of internal distortion after charging; and the charging components had to be low cost and therefore low power devices.

The maximum ratio of forward charge to reverse charge was set to 4:1 – but in fact any ratio around this figure will work. As charging continues, the size of the forward pulse is gradually lowered to keep within the cell's charge-acceptance limits as explained above, and the ratio of forward charge to reverse charge reduces, until at 1.68V it is 1:1. That is, the energy contained in each forward pulse equals the energy contained in the reverse pulse at this cell voltage. The oscilloscope screens of Fig. 2 show what happens. Note the period of this quasi-square wave is not quite even.

If left to itself, the cell/circuit combination would settle at a 1:1 per ratio at 1.68V and stay there indefinitely. The circuit so far could be regarded as a complete charging circuit, requiring no more components. However, leaving the cell in such a state for any length of time is not desirable because each forward and reverse pulse represents a charge/discharge cycle and there is a limit to the number of these the cell can take.

Also, failure of just one component of the circuit might result in overcharging, so for safety's sake and to preserve the life span of the cell, a further circuit has been added to stop charging. This consists of a simple comparator which effectively stops both forward and reverse pulses just before 1.68V. The voltage chosen is 1.62. This an arbitrary voltage which I found gave a good charge to the cell. Other voltages could be chosen, but voltages lower than this tended to give shorter charging times and not such a good charge. Voltages too close to 1.68V gave erratic turn-off – the reasons for which are mentioned later.

### Circuit details

Op-amp  $IC_{1a}$ ,  $Tr_1$  and  $Tr_2$  provide the 1.68V ceiling voltage for the forward charge pulse. The voltage reference is derived from the 5V power line provided by the 7805 regulator by means of resistor chain  $R_1$ ,  $R_3$  and  $VR_1$ .

Exactly how the ceiling voltage is set is described later, but adjustment is carried out with preset pot  $VR_1$ . The forward charging current is provided at mains frequency every half-cycle to this circuit by rectifier diode  $D_2$  from the 6V ac transformer line. On its own, this circuit would generate hf oscillations every half cycle, so this tendency is suppressed by  $C_1$ .

Since each of two cells takes a forward pulse every half-cycle, to balance the transformer these two circuits are used back-to-back with centre-tapped transformer.

To limit the maximum current that the above circuit can supply to around C/35,  $Tr_3$  and  $R_6$  are added. Transistor  $Tr_3$  simply clamps the base of  $Tr_2$  at a pre-set current level determined by  $R_6$ . However, the circuit would try to supply this current at all voltages up to the 1.68V limit, so  $R_1$  added to introduce a gradual tapering-off of current as the cell voltage rises. The internal resistance of the cell cannot be relied on for this.

The reverse-charge part of the per cycle is

### Safety issues

Safety has to be seen in context. For example, we use that most flammable of fuels, petrol, to power our most popular method transport, but few refuse to travel by car just because of the fire risk. The car makers do not put a warning about fire-risk on cars.

We use a lethal voltage instead of a safe one around the home to power various devices – and we actually hold some of these devices in our hands to operate them!

The risk in both cases is universally accepted despite the fact that people do occasionally come to grief, because the usefulness is great and the risk small when devices are used correctly.

Compared to the two examples above, any risks posed by the techniques put forward must be regarded as minuscule, when approached properly. From the tests conducted, and the continuous use this charger has had over many years, the risks appeared to be acceptable. Any risk would seem to come from random component failure and misuse.

In a well-ordered technology-based society, the warning on the side of alkaline cells should be amended to, "Do not recharge in an unsuitable charger" It would then be technically correct, which it is not at present.

provided by  $Tr_4$  and  $R_7$ . While the cell is being charged  $Tr_4$  is turned constantly hard on via the led and  $R_8$ . During the forward pcr pulse, the small reverse-charge current is swamped or cancelled out by the much larger forward current. This is a simpler and cheaper concept than one which uses a second pulsing circuit for the reverse pulse and is easy to turn off at the end of charging.

While charging is in progress, the led is on, and can be used to show when the cell is under charge, but there are better methods as discussed later. Different values of  $R_6$ ,  $R_1$  and  $R_7$  are used for cell sizes D, C, and AA. Table 1 shows values for these sizes.

Op-amp  $IC_{1b}$  and its associated components form a conventional comparator to detect the end of charging. It can be pre-set by  $VR_2$  to trip at around 1.62V. Voltage on the cell cannot be monitored directly by the comparator because of the small ripple voltage across the cell when being pulsed. The cell voltage is therefore filtered by  $R_8$  and  $C_3$  before being applied to  $IC_{1b}$ .

The comparator is biased towards the 'off' position, i.e. output low, so that once turned off by a voltage over the limit, it cannot be turned back on again except by manually-operated switch. This arrangement is needed because once a fully charged cell has tripped the comparator, the cell voltage soon drops and could turn the comparator back on to give more, unnecessary charging.

Once the comparator is tripped,  $Tr_4$  is turned off via  $R_9$  and the reference voltage presented to  $IC_{1a}$  is lowered via  $R_4$  and  $D_1$ . This effectively stops charging. In this state only small semiconductor leakage currents around the cell charging circuit are present, which can be

disregarded for practical purposes. However it would not be advisable to leave the cell in the charger for long periods, several weeks for example, because of these leakage currents.

The charge sequence can be started again by pressing momentary push-switch  $S_1$  which simply overcomes the bias of the comparator.

The IC chosen for this circuit is the *LM324* quad op-amp – a cheap temperature compensated device which can do both functions of reference and comparator reasonably well. It makes a two-cell charger very economical.

**Setting up the circuit**

First, comparator  $IC_{1b}$  is disabled by being turned on, i.e. output high, by  $VR_2$ . A high-value low-leakage electrolytic capacitor is then substituted for the cell. I used 50,000 $\mu$ F computer-grade type which seemed to work very well.

At power on, preset pot  $VR_1$  is now adjusted to give 1.68V on  $C_2$  using a high-impedance dvm. The capacitor acts in approximately the same way as a cell, that is, as a store of electrical energy, so you can say that at 1.68V the energy in from the forward pulse equals energy out from the reverse pulse.

This method ignores the small amount of ripple on the large capacitor about 10mV peak. After this preliminary setting it is best to check the balance point with a real cell to ensure the voltage never rises above 1.68V, before you set the comparator. You could do the setting-up with a cell, but it would then take a much longer time, perhaps several hours, to reach the balance point, whereas you can get to it very quickly using a capacitor.

Having done this, the comparator can be set to trip at around 1.62V by observing the out-

put led while adjusting the voltage on the large capacitor to this value with a variable resistor. While you have the dvm at hand, the comparator voltage swing should be checked to ensure correct operation. This comparator will trip within 10mV of the set voltage.

The charger is then ready to use.

**Charge indication methods**

Although the led in series with  $R_8$  can show when charging is in progress, it cannot show what point has been reached. Small inexpensive moving-iron meters are on the market which could be used at point M in the circuit.

A meter is the best indicator with small cells. Alternatively, for D and C cells, a filament lamp-bulb can be successfully used. This is set for full brightness with a discharged cell – i.e. at the short-circuit current – and just glowing at the balance point. A parallel resistor may be needed with some bulbs. For this purpose, I have used a T1 1.5V 200mA, which is difficult to obtain, and a MES lens-end 1.2V type which is more readily available at 200mA and 300mA. Performance can be improved with an ntc thermistor in parallel instead of a resistor.

**Using the charger**

The charger has been proved from 15°C to 25°C so use outside this range is not recommended. As stated, there is no temperature compensation.

Also, the construction has to be such that the cells and circuit are kept within temperature limits by free ventilation. This means an open construction with plenty of slots for air circulation.

The comparator circuit is prone to trigger prematurely when approaching full charge if current spikes are allowed in from the mains, so a mains filter is essential. For the same reason, the whole circuit should be in a metal box to reduce incoming emi, although the absolute need for free ventilation will nullify most of this benefit. The metal box can be a safety feature if there is any remaining doubt about bursting cells. Also, any thermal effects from  $Tr_2$  can be reduced by using the metal box as the heat-sink.

A spike from a comparator rapidly turning off can trigger a neighbouring comparator to turn off before its time, if that was also in the sensitive region near the end of charging. To prevent an abrupt turn-off, capacitor  $C_6$  has been added.

If you live in an area of high interference, it may be necessary to current-slug the comparator with capacitors  $C_4$  and  $C_5$ , and the reference with  $C_1$ . The value chosen depends on how severe the interference is. Start with 1 $\mu$ F for  $C_4$  and  $C_5$  if you experience premature turn-off. These capacitors *must* have negligible leakage current.

Drift with age may be a problem if not detected. As a result, it would be reasonable to check the two important voltages with a meter now and then. I suggest a check after the first couple of cycles and then every six or twelve months.

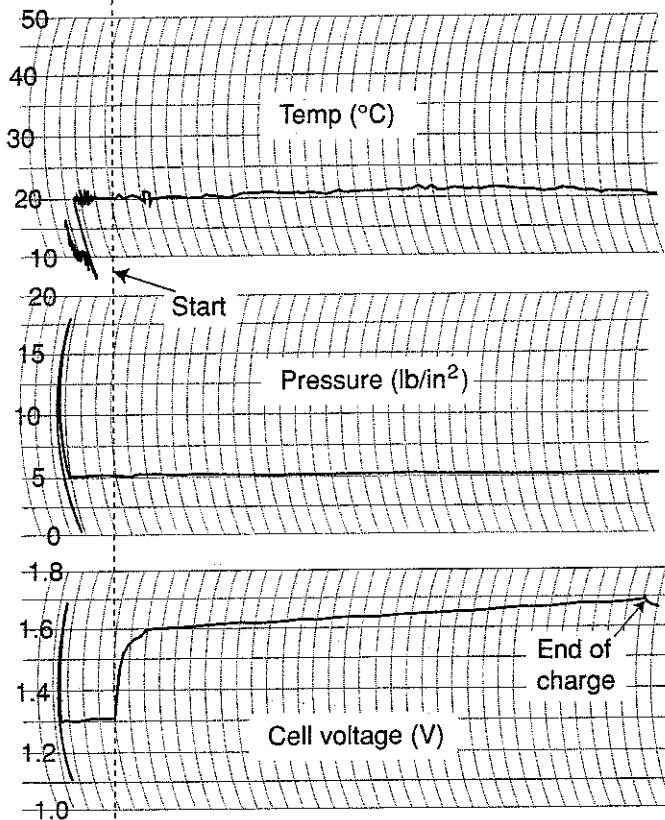


Fig. 4. Traced chart recordings of characteristics of an alkaline cell under charge using the circuit of Fig. 1. These show that temperature and pressure rise are negligible.

### Safety

Because of the likelihood of counter-claims about safety from battery manufacturers trying to protect their market, more than usual effort was put into checking the safety of this design.

There are two main areas that could pose a risk. Firstly, there is the possibility of internal pressure arising from an accumulation of gases caused by electrolysis. This is the most likely cause of leakage if recharging continues when the cell is fully charged. But it could occur at any point on the recharge cycle if the cell was given a current larger than the cell's charge-acceptance. This could be caused for example by using the charger at low temperatures.

Secondly, a risk could be posed if the temperature during recharge rose to excessive levels. Leakage could come from the expansion of any gases already inside the cell – from reverse-charging for example – or from steam being formed if the cell got hot enough for this. These two potential risks are examined in turn.

Regarding the first point, internal pressure, three methods were used to check internal cell pressure during recharging. I noticed that whenever a cell leaked due to internal pressure from deliberate abuse, it bulged slightly at the ends, and it was possible to measure this small

expansion with vernier callipers. In fact, a bulge could be easily detected before any leakage occurred. Both bulge and leak conditions could be readily achieved by deliberately trickle-charging the cell.

This formed the basis for the first method. I measured cells with callipers – with insulated jaws of course – before, during and shortly after being recharged in the P24 but there was never any size increase over many cycles. It was clear that there was no detectable pressure developed by normal recharging.

The second method I used to check pressure was to attach a bourdon type pressure gauge to the cell with an adapter. I did this to be able measure directly the pressure, if any, that was being developed inside the cell. The cell was firstly pressurised via a schraeder valve and left for a few hours to confirm the cell was gas-tight and then given several discharge/recharge cycles.

The gauge never showed any significant pressure increase or decrease. As the volume of the released gases is small, I tried to make this rather clumsy technique more effective by filling the 'dead space' in the gauge with silicon oil, plugged with light silicon grease to stop it escaping and contaminating the cell. But it still never showed any pressure increase.

The gauge was refined in a third, more sensitive test by attaching an electronic pressure sensor to a chart recorder so that the whole cycle could be recorded. The arrangement is shown in Fig. 3. This third method again showed no detectable pressure increase.

Regarding temperature rise, it was noted by Hallows that temperature rise with pcr is very small, in contrast to other methods of recharging. My tests confirmed this. A temperature sensor was attached to the metal jacket of the cell during cycling and connected to a chart recorder. As Fig. 4 shows there was no significant rise in temperature.

The overall conclusion from these tests was that the P24 simply does not create internal pressure in cells. Cells in many conditions from brand-new to totally dead were used in the tests to cover the range of possibilities in real life.

A post-mortem was conducted on cells that had been cycled to exhaustion to check if there had been any physical changes inside the cell. The cells were sliced up on a miniature milling machine with a 0.5mm slitting saw, which did not disturb the contents too much. In no case was there any tell-tale sign of electrolyte leakage.

No distortion attributable to internal pressure was observed. ■

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