

THE CHARACTERISTICS AND USE OF LEAD-ACID CAP LAMPS.

by M.F. Cowlshaw

Summary

It was 1885 when the first portable rechargeable lamp was invented. The lead-acid cap lamp we know today has evolved in the ninety years since then, and has a high capacity together with many other advantages.

This paper describes the construction and characteristics of these lamps, and discusses possible modifications, the use, and the maintenance of the most common types of lead-acid cap lamps.

1. Introduction

Lighting is vitally necessary underground, and it is usually very important to ensure that there are no failures on a caving trip, and that the lamp used is as efficient as possible – both for safety and for good morale.

Despite this, cap lamps of all types are often sadly abused, and the literature available in caving magazines is often inadequate, and sometimes contradictory.

Inevitably the standard and types of lamps used by cavers is dictated by and lags behind those used commercially. Hence the change over from alkali to lead-acid lamps by the NCB is now being followed by cavers. It seems likely that lead-acid lamps will be the main form of portable rechargeable lighting used underground for some time to come, despite the competition from more modern (and more expensive) types.

The lead-acid battery has many advantages over other rechargeable batteries (Neill: 1965), the most important for cavers being: fairly high power to weight ratio; low cost; high electrical efficiency (Important where lamps are being recharged from vehicle batteries, for example); flat discharge voltage characteristics; simple self-service charging capability; and finally, the electrolyte is far less dangerous than that used in alkali batteries, although the acid will affect the strength of nylon equipment. On the other hand, lead-acid batteries are perhaps more susceptible to incorrect charging than alkali types, though if the right method is used overcharging cannot occur and reliable performance should be obtained.

This paper describes in detail most aspects of the use and care of lead-acid lamps, and I hope will clear up many of the misunderstandings that exist concerning these lamps. In addition a small amount of theory is included, as is a discussion on some possible modifications.

2. Brief History

The principle of the lead-acid rechargeable accumulator was first applied by a German physicist named Sinsteden in 1854. His simple cell was greatly improved to give greater capacity, first by Planté in 1860, and also by Fauré in 1881. It was Fauré who developed the pasted plate from which modern negative plates have evolved (Smith: 1971). Shortly after this, in 1885, J.W. Swan patented the first rechargeable lead-acid hand lamp – this weighed about 4.5 Kg, and incorporated a bulls-eye lens.

In 1912 the increasing demand for electric lighting underground led to a prize being offered for the best design (Barnard: 1936). The most successful entry was a Ceag 2 volt lead-acid lamp, though there was no outright winner. However, two volt bulbs are inherently inefficient (as the short filament length implies that a high percentage of the power available is dissipated as heat from the filament supports), and so it became obvious that four volt lamps should be designed.

The first widely used became available in about 1930 – this weighed over 4 Kg, and used a 1 Amp Argon-filled bulb which gave a light output of 36 lumens. In 1936 the Krypton-filled bulb was introduced, giving as much as 20 percent more light than argon filled types.

The Oldham 'Wheat' cap lamp was launched in the 1930s, and was very similar in looks to the hard rubber-cased lamps we know today. Successive models of Oldham batteries have become available since the war, the types most commonly used by cavers now being models Y and R. The most recent Oldham battery to be introduced is the model T, which probably represents the state-of-the-art as far as batteries for miners' lamps are concerned. It is hoped that these will soon make their appearance on the caving scene.

The well known 'Exide Triclad' first made its appearance nearly twenty years ago, and is also widely used, being interchangeable with Oldham types. It is usually part of the Ceag CgL2 lamp.

Modern lamps have a capacity of over 10 Amp-hours, weigh less than 2.5 Kg, and are extremely reliable if correctly treated.

Note on definitions

The terms describing lighting sets and their constituent parts are often very loosely applied in caving circles. The following definitions are used for the purpose of this paper:

Cap lamp; lamp : The complete lighting set.

Battery : The electricity storage unit, usually carried on a belt and consisting of two lead-acid cells.

Cell : One lead-acid unit consisting of positive and negative plates, and nominally two volts.

Headset : The part that normally attaches to the helmet.

3. THE LEAD-ACID BATTERY

3.1 General Description

A cell in a cap lamp battery consists of three plates held apart by porous separators and surrounded by a strong shock resistant case which also serves to contain the acid electrolyte (see Fig. 1a). The centre plate is the positive plate which when charged is mainly lead dioxide (PbO_2). The construction of modern positive plates is tubular, each tube — as shown in Fig. 2 for example — consisting of an antimonial lead alloy spine (for strength) surrounded by the active material which is packed as a powder into the outer sleeves that hold it together. The two outer plates are formed from the negative active material, lead (Pb). These plates are described as being of pasted construction since part of the manufacturing process consists of making a paste of lead compounds, sulphuric acid, and various additives, which are then formed onto the basic grids of the plates (Neill: 1965, Roberts: 1958).

Modern separators are highly absorbent in order to reduce as far as possible the free electrolyte in the cell, and are now exclusively synthetic. Their thickness means that the internal resistance of a cell is fairly high when compared to other types of lead-acid cells — being about 0.05 ohms.

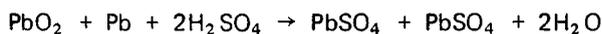
The cases of batteries are moulded in hard synthetic rubber or plastics such as polycarbonate. Incorporated in all cap lamp batteries are topping-up holes and non-spill vents which allow any gas released during charging to escape, but keep acid inside the cells even if the battery is inverted. The acid electrolyte is approximately 20% sulphuric acid of high purity, and batteries are normally protected by a two or three ampere fuse.

The non-spill vents are only effective if the electrolyte level is correct. Acid leak from the vents may be noted after the battery has been immersed in water, since the cooling of the air inside the battery causes water to be forced in, hence diluting and contaminating the electrolyte. The electrolyte level rises, so leakage occurs, especially during charging. This can be avoided by blocking or covering the vents before immersion (taking care that any thing used cannot be sucked up into the battery). The vents must be cleared before charging.

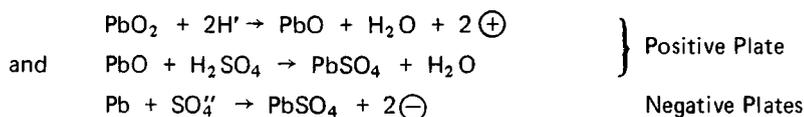
3.2 The Discharge Process

A fully charged cell has the positive active material PbO_2 , the negative active material Pb, and the electrolyte at its strongest with a specific gravity of about 1.29 (pure water has a s.g. of 1.00). When put on load — that is, when the lamp is switched on — each cell will begin to discharge from a starting voltage of nominally 2 volts. During discharge, the positive and negative plates are transformed slowly into lead sulphate (PbSO_4) as shown diagrammatically in Fig. 1b. The sulphur in this compound must of course come from the sulphuric acid, so the electrolyte becomes more diluted with the s.g. dropping eventually to about 1.10 during a normal discharge. In general-purpose lead-acid batteries the specific gravity is a very accurate guide to the state of discharge, however in cap lamp batteries there is very little free electrolyte, and so measuring the s.g. is not usually a practical proposition.

The chemical formula for the discharge process is simply:



or more fully:



(The \oplus and \ominus symbols represent the electric current.)

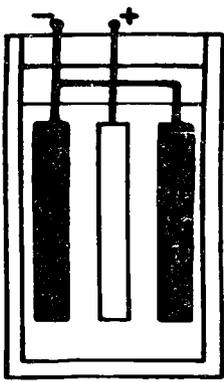
During this process the internal resistance of a battery rises from about 0.1 to 0.15 ohm, the actual value depending on its condition and age — in general a battery which is old or in bad condition will have a higher internal resistance.

A typical discharge curve is shown in Fig. 3. Batteries should not normally be discharged below 1.7 volts per cell at which point the main beam will be noticeably dimmer than full brightness. If discharged below this voltage, the battery should be recharged as soon as possible as otherwise sulphation will become pronounced far more quickly than usual. In addition sulphation will occur in normal use if a battery is left in a discharged state for long periods — see section 3.3.

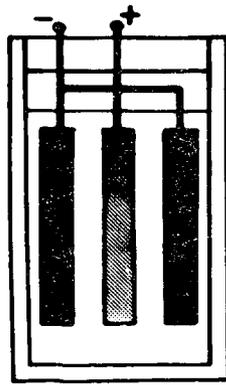
It will be seen from the discharge curve that the battery voltage remains close to 4 volts for most of the time. This is an important point as it means that bulbs can be used close to their optimum operating point for most of the period of discharge, which makes for high lighting efficiency.

The electrical power efficiency of a lead-acid battery is extremely high. 75% of the power put in during charge may be used on discharge, which is especially important where lamps are being charged from vehicle storage batteries. The amp-hour efficiency (Amp-hours output/Amp-hours input) is even higher — typically 90%. The efficiency and capacity of a battery is reduced at low temperatures, both being as much as 10% less at 0°C than at 15°C.

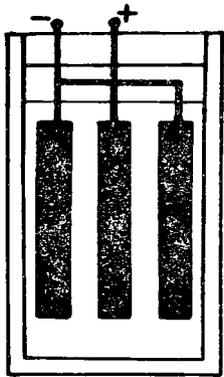
Occasionally during an unexpectedly long stay underground it might be necessary to exhaust a battery. A fact that may be unknown to some is that if such a battery is switched off and left to 'recuperate' for an hour, some chemical recombination occurs, and the lamp will then be found to give as much as 40 minutes of light on main beam. This process may be repeated — with rapidly diminishing returns. This treatment will cause the electrolyte s.g. to reduce to near that of water. When put on charge, the battery will become warm but provided it is recharged immediately no serious damage should occur (Neill, 1974, Private communication).



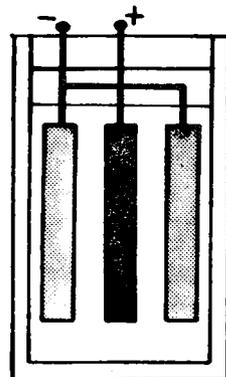
a) Fully charged cell.
 +ve plate PbO_2
 -ve plates Pb
 Electrolyte at strongest.



b) Discharging.
 Increasing $PbSO_4$
 in all plates.
 Electrolyte decreasing
 in strength.



c) Discharged.
 All plates
 maximum $PbSO_4$
 Electrolyte at
 its weakest.



d) Charging.
 +ve plate increasing PbO_2
 -ve plates increasing Pb
 Electrolyte increasing
 in strength.

Figure 1. Stages in the discharge/charge cycle.

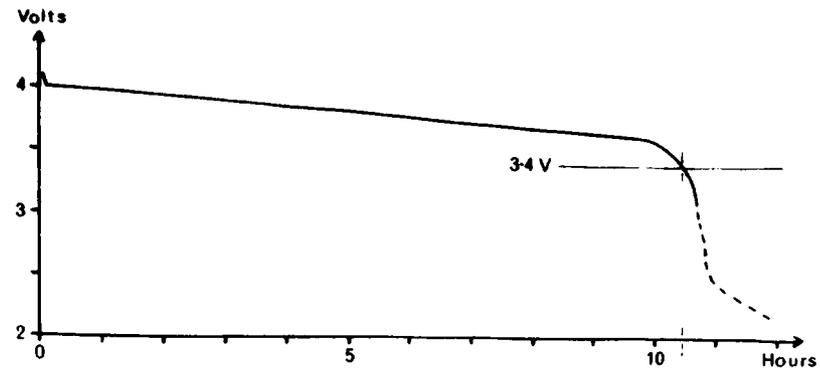


Figure 3. A typical discharge curve.

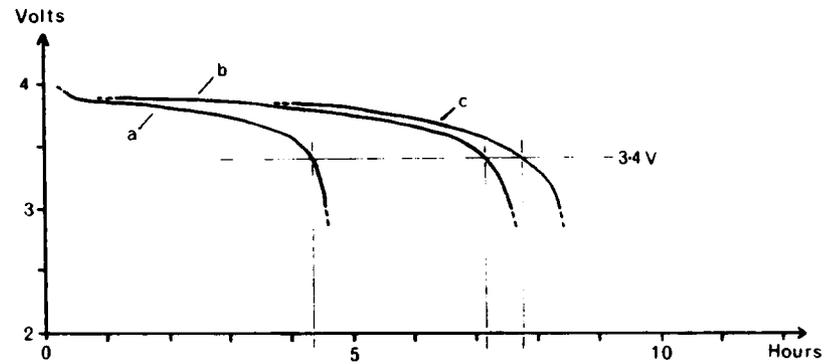


Figure 4. Discharge curves of a sulphated battery.

- a) initial discharge curve.
- b) after a reconditioning charge.
- c) after a second reconditioning charge.

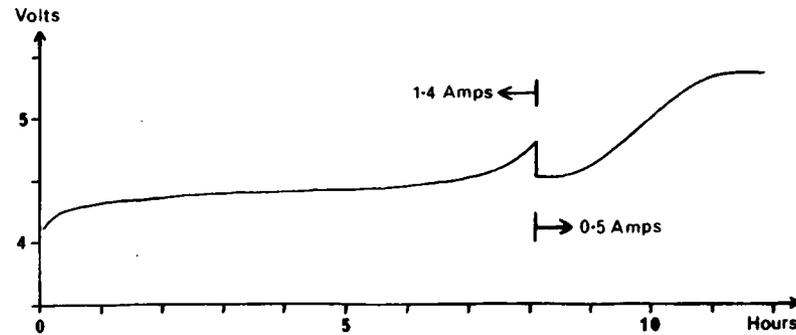


Figure 5. Voltage curve for constant current charging.

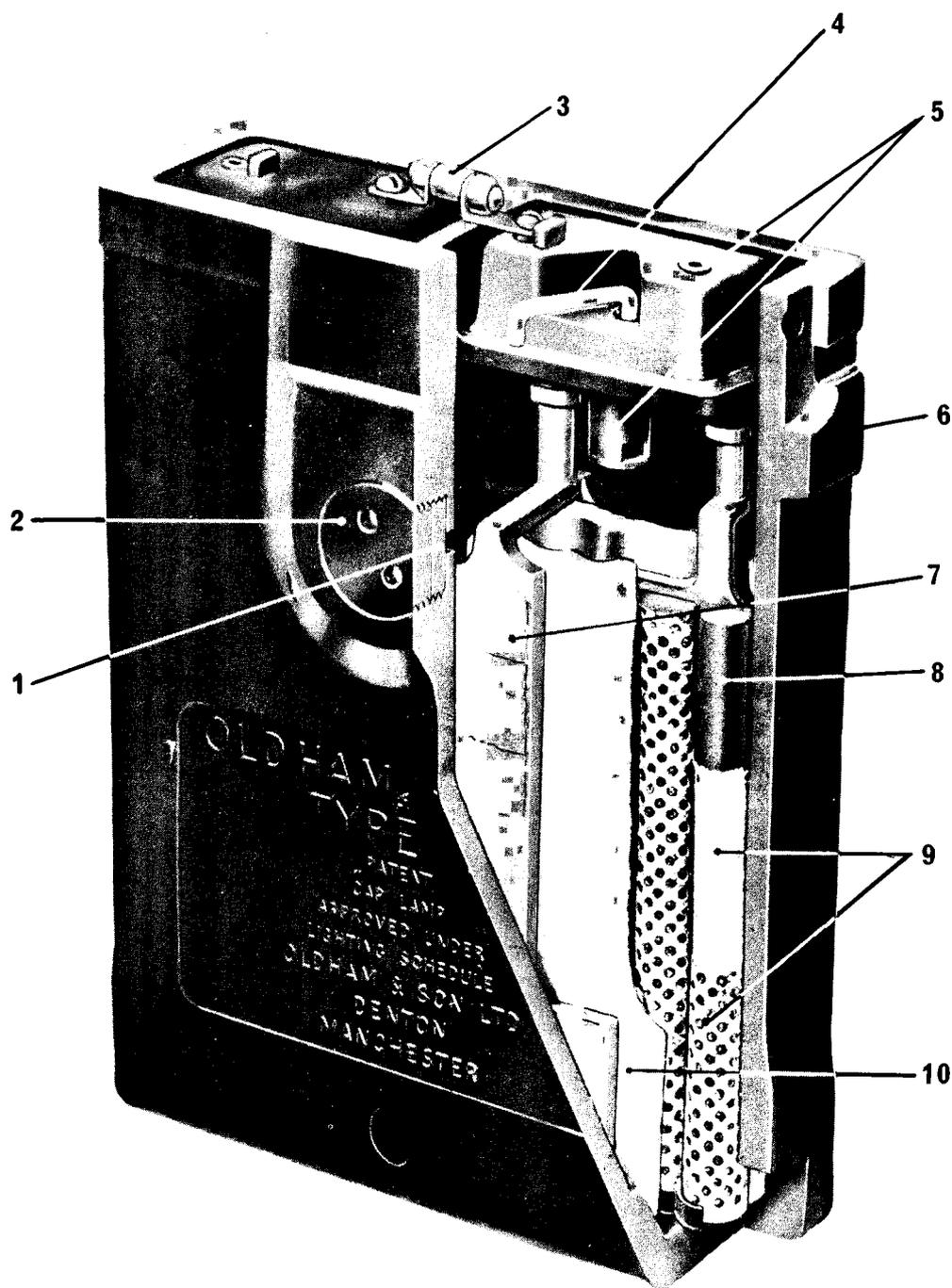


Figure 2. Sectional view of the Oldham type 'R' battery.

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| 1) Rubber seal. | 6) Toughened hard rubber container. |
| 2) Removable plug for topping up. | 7) Negative pasted plate. |
| 3) Fuse. | 8) Positive active material. |
| 4) Gas vent link. | 9) Porous sleeves. |
| 5) Rubber lid with non-spill device. | 10) Separator. |

Finally, an increase in the capacity of a new battery of about 10-20% will be noted over the first few discharge/charge cycles. This is analogous to 'running in' and is quite normal.

3.3 Sulphation

Lead sulphate is formed in the normal course of events during discharge. It takes up more space than the active material, and hence the porosity of the plates is reduced (Smith: 1971). The amount of sulphate may become excessive due to repeated over-discharging without adequate recharging, by leaving the battery in a discharged state for long periods, by use at higher temperatures (over 45°C), or by adding excessive acid to the electrolyte. Should this happen, the porosity of the plates will be reduced to such a degree that the electrolyte is unable to reach the plates to the normal extent, which causes a reduction in capacity. In the extreme case the battery will not accept a charge at all and is therefore useless.

When sulphation occurs, the internal resistance rises due to the loss of porosity, and the sulphate cannot be wholly reconverted by charging in the normal manner as described in section 7.3. There is fortunately a cure for mild sulphation — a long slow charge of a constant half amp for about 30 hours will normally cause an improvement. Fig. 4 illustrates this. Curve *a* shows the discharge curve of a badly sulphated battery, which also had one damaged cell. As can be seen, the discharge time (down to 3.4 volts) was about 4.3 hours. A remedial charge as described was then applied. After this the discharge time can be seen to have substantially risen to about 7.2 hours (curve *b*). A further long constant current charge was then applied which resulted in a further improvement in the discharge time of half an hour — a smaller increase (curve *c*).

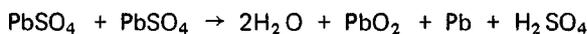
The gradual tail off at the end of the curves is indicative of a damaged cell, and when the acid was restored to its proper strength in that cell the discharge curve regained its characteristic knee.

Hence an apparently unusable battery was restored to service.

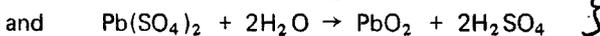
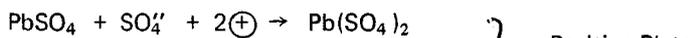
3.4 The Charging Process

A discharged battery has its plates chemically similar with a high amount of lead sulphate. The electrolyte is at its most dilute (Fig. 1c). The process of charging returns the plates to their original state by passing an electrical current through the cells of the battery in the direction opposite to that of discharge. During this process the electrolyte becomes progressively stronger, the positive plate is converted to PbO₂, and the negative plates return to being spongy lead (Pb).

The simple chemical formula for this is:



or more fully:



As might be expected the internal resistance of the battery drops during charging as the plates regain their porosity.

When a discharged battery is taken off load, its voltage rises to 4 volts in a matter of minutes. If a constant current of 1 amp is passed through it, the voltage will initially rise to about 4.2 volts and then rise more slowly until the battery is 80% charged and the voltage is around 4.6 volts. At this point profuse gassing begins, and the voltage starts to rise sharply. If the current is now reduced to about half an amp (the 'finishing current'), gassing will almost stop, and the voltage will drop slightly but then begin to rise steeply, eventually levelling off at about 5.3 volts as shown in Fig. 5. The battery is then fully charged.

This constant current method of charging is not now used commercially as it is somewhat cumbersome since the current has to be reduced at the appropriate moment, and then be switched off when the battery is fully charged to prevent overcharging.

A modified constant potential (voltage) method is now used exclusively in NCB lamp rooms. This system works by putting a constant 5 volts across a low value resistor and the battery which are in series. The purpose of this ballast resistor is to limit the current that flows when the battery is first put on charge. In practice this resistor is often incorporated in a moving iron ammeter which serves to indicate the charging current. The voltage drop, *V*, across the ballast resistor is given by:

$$V = 5 - (E + I.r) \quad (3.4.1)$$

where *r* is the resistance of the cable plus the effective internal resistance of the battery; *E* is the battery voltage if momentarily taken off charge; and *I* is the current that flows through the battery.

I is therefore given by:

$$I = \frac{5 - E}{1 + 3r} \quad (3.4.2)$$

(if the ballast resistor is a third of an ohm)

$$\text{or; } I = \frac{3(5 - E)}{1 + 3r}$$

E, the initial voltage of a battery, will be very close to 4 volts, and *r* will be about 0.2 ohms for a lamp in normal condition, so the initial charging current will be 1.8 amps. In practice, the initial charging current for a discharged battery will be found to vary between 1.5 and 2.0 amps due to tolerances in the value of the ballast resistor etc.

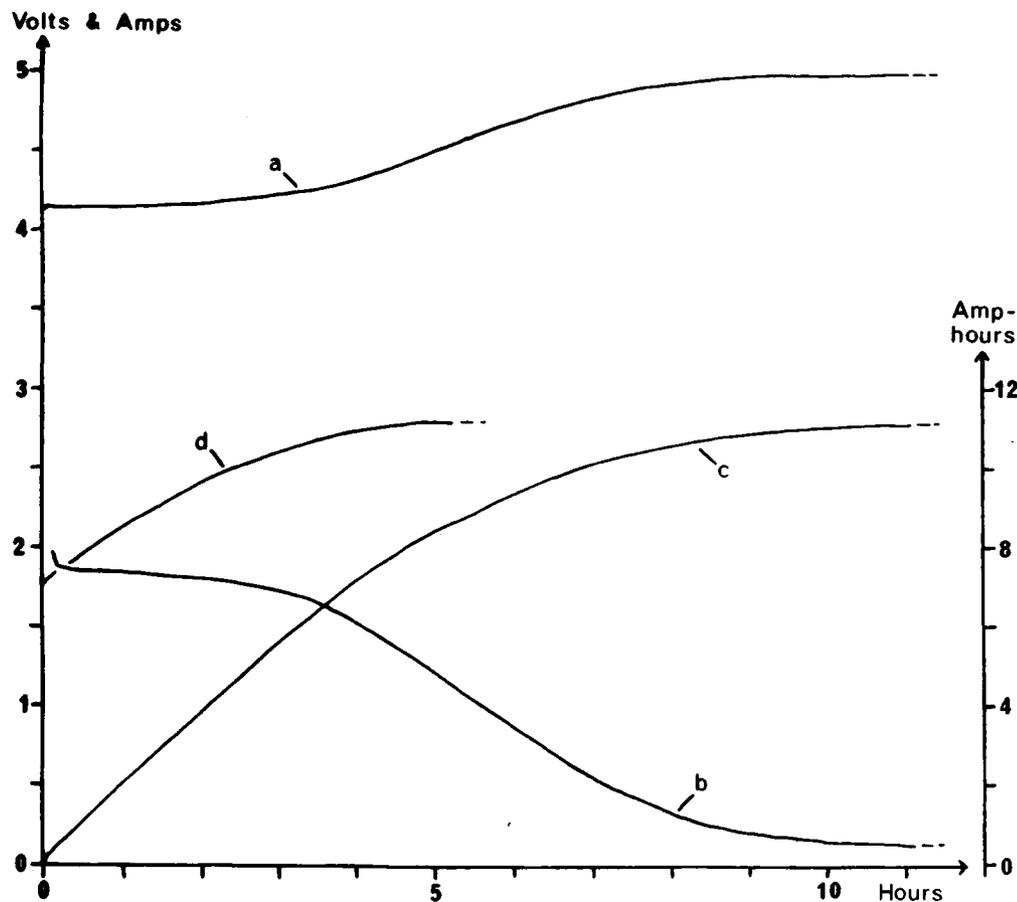


Figure 6. Modified constant potential charging.

- a) Voltage curve. (E).
- b) Current curve.
- c) Amp-hour curve.
- d) Amp-hour curve for a partially discharged battery.

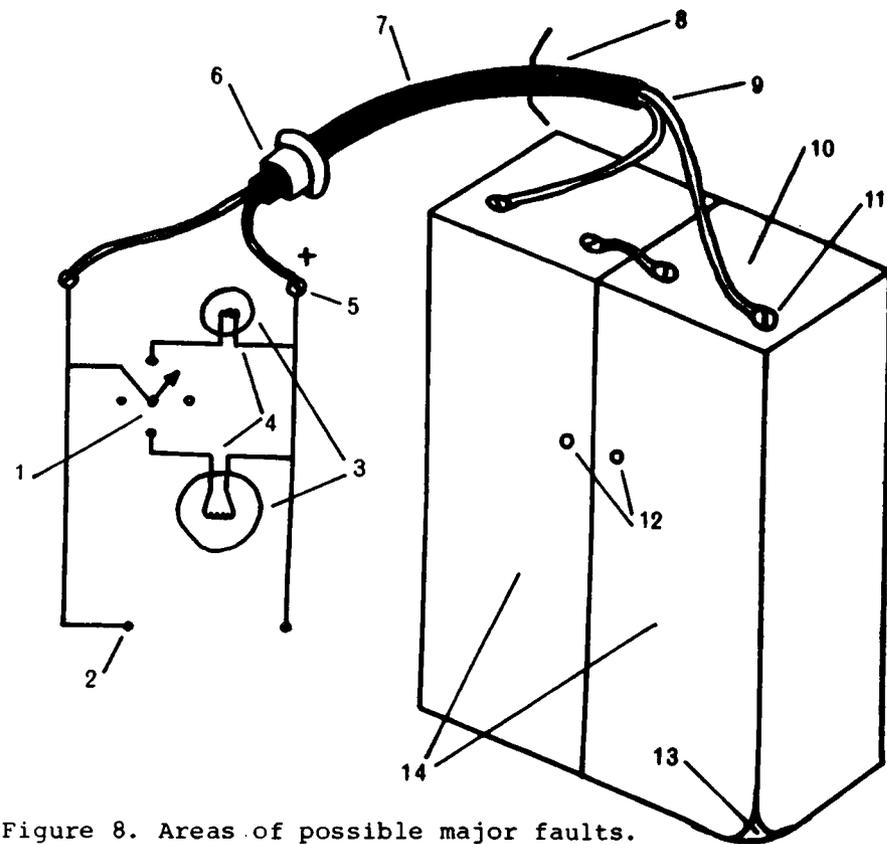


Figure 8. Areas of possible major faults.

- 1) Headset switch contacts.
- 2) Charging switch.
- 3) Bulb failure.
- 4) Headset conductors or bulb contacts corroded.
- 5) Cable connections in headset faulty.
- 6) Water seal and cable grip inefficient.
- 7) Cable: open or short circuit, or high resistance.
- 8) Cable grip inside battery cover faulty.
- 9) Wires corroded or damaged.
- 10) Acid leak at cell lids.
- 11) Contacts and screws on tops of cells corroded.
- 12) Acid leak due to faulty seal; or electrolyte level low.
- 13) Corners worn through.
- 14) Sulphation of cells.

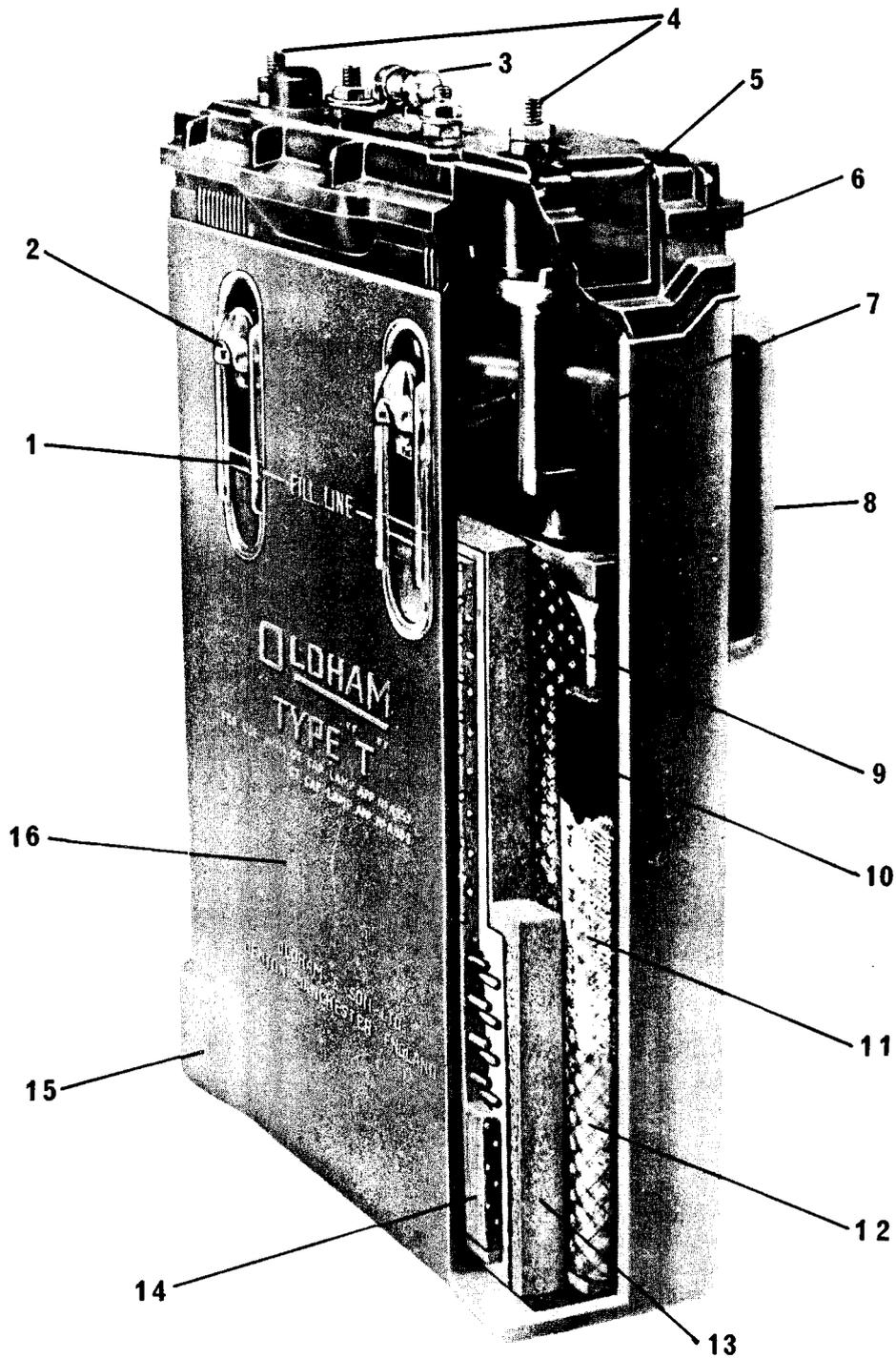


Figure 7. Sectional view of the Oldham type 'T' battery.

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|-------------------------------------|-------------------------------------|
| 1) Visible electrolyte level. | 9) Antimonial lead spine. |
| 2) Venting and topping up aperture. | 10) Positive active material. |
| 3) Fuse. | 11) Woven glass fibre inner sleeve. |
| 4) Battery terminals. | 12) Perforated PVC outer sleeve. |
| 5) Post seal. | 13) Absorbent separator. |
| 6) One-piece Polycarbonate lid. | 14) Negative plate. |
| 7) Anti-spill device. | 15) Toughened corner. |
| 8) Integrally moulded belt loop. | 16) Polycarbonate container. |

The effective internal resistance drops to 60% of its original value during charging, and E rises to 5 volts. The voltage/time curve is shown in Fig. 6a, and so the charging current curve is as shown in Fig. 6b. It will be seen that when the voltage has risen to nearly 5 volts — that is, when the battery is fully charged — the current, I, will have dropped to about 100 milliamps. A battery can take this current for one or two weeks (A.G. Neill: 1974; Private communication) so there is evidently very little chance of overcharging as a lamp can be left on charge for several days.

It is when other methods of charging are used that damage can occur. The dangers are firstly overheating, caused by charging at too high a current; and secondly overcharging, which could cause the positive plate to shed active material, hence eventually reducing the life of the battery. The first of these may be avoided by ensuring that the charging current is always kept below 2.5 amps. Overcharging can be avoided either by using the recommended constant potential charging method, or, if another method has to be used due to force of circumstances, the charging current should be kept low enough to prevent excessive gassing, which is audible.

Excessive gassing will occur whenever too high a current is passed through a part charged battery. It takes the form of hydrogen and oxygen which is emitted from the plates at high velocity — and therefore tends to take some active material with the bubbles. The highest current that should be passed through a two cell battery of voltage E while on charge is given by the formula:

$$I_{max} = 8.5 - 1.5E \quad (3.4.3)$$

This is in effect the formula for a taper charge from 2.5 amps down to 1 amp. This can be utilised to give a fast emergency charge to a battery — see section 7.3.

It is important when charging a battery to know how much time is required to recharge it completely. While it is impossible to specify exact figures, as individual batteries can vary so much with age and condition, there are some general rules. The first point is that the amp-hour efficiency of lead-acid batteries is very high, viz. about 90%. This means that if a battery is discharged for ten hours at one amp, that is, for ten amp-hours, then about eleven amp-hours will be needed to recharge it.

Secondly, most of the recharging is done in the first part of the charging process when the battery voltage is still fairly low. For example, about 85% of the charge is restored within 70% of the charging time.

Thirdly, charging time will be increased during cold weather, being about 10% longer at freezing point than at 10°C.

Lastly, with constant potential charging, for a given state of discharge the charging time is very nearly inversely proportional to the starting current, which is the current that flows a few minutes after the lamp is put on charge.

A mathematical approximation for the charging current during constant potential charging has been determined empirically and was found to be given by:

$$I(t) = I_s \left(1 - \frac{0.9t}{T} + 0.2 \sin \frac{2\pi t}{T} \right) \quad (3.4.4)$$

where I_s is the starting current; t is the time from the beginning of charge; and T is the total time required for the charge. Units are amps and hours.

T and I_s are nearly inversely proportional, as stated above, the relationship being approximately:

$$T \cdot I_s = \frac{2Ah}{1.1} \quad (3.4.5)$$

where Ah is the number of amp-hours required to recharge the battery. The main formula (3.4.4) is most accurate when the battery is initially fully discharged, and a typical value of A_r in this situation is 11, so $T \cdot I_s = 20$. From this the charging time for a given starting current may be calculated. For instance, for $I_s = 1.8$ amps, the charging time will be 11 hours.

The formula to find $A(t)$, the amp-hours restored to the battery after t hours on charge, may be found by integrating equation (3.4.4) as the area under the current curve up to a given time t is equal to the amp-hours restored in that time. This gives:

$$\begin{aligned} A(t) &= \int_0^t I(t) \cdot dt = I_s \left(\int_0^t 1 \cdot dt - \frac{0.9}{T} \int_0^t t \cdot dt + 0.2 \int_0^t \sin \frac{2\pi t}{T} \right) \quad (3.4.6) \\ &= I_s \left(t - \frac{0.9t^2}{2T} - 0.2 \left(\frac{\cos 2\pi t}{T} - 1 \right) \right) \end{aligned}$$

This curve is shown for a value of $T = 11$ in Fig. 6c. It will be noted that at the end of the charging period 11 amp-hours have been restored to the battery, as specified. It will also be seen that the main bulk (92%) of the charging is done during the first 70% of the charging period. This implies that even if the full time is not available for charging, the battery can often be almost fully recharged.

When only a few amp-hours need to be restored to the battery, the $(\cos\theta - 1)$ term in formula (3.4.7) becomes less important, and a reasonable approximation to the amp-hour/time curve can be made by ignoring it altogether. If in addition we substitute for T from (3.4.5), we get:

$$A(t) = t \cdot I_s \left(1 - \frac{t \cdot I_s}{4Ah} \right) \quad (3.4.8)$$

which may be used to draw the curve or to calculate the percentage restored in a given time. A typical curve is shown in Fig. 6d, for $Ah = 4$ hours. I_s would be about 1.5 amps.

Finally, when a battery is taken off charge, its voltage will be nearly 5 volts. This implies that if the lamp is switched on immediately, it will be overrun by 25% which could lead to a premature failure. In practice, a lamp is normally left for a few hours before use, and so the voltage will have returned to its normal value of about 4 volts.

3.5 Types of Battery

There are two basic types of battery at present in use by cavers. These are the Oldham type, being mainly models Y; YR; and R, the latter perhaps being the most common; and the Exide Triclad, mainly type F2. The Oldham model T has not yet reached the caving scene in significant numbers, but a description is included here for completeness.

The Oldham hard rubber-cased models are all very similar in appearance, though as might be expected, the more recent the model, the more improvements that are incorporated, and the higher the capacity.

The model R (Fig. 2) is the best of these types available, and is very robust. The terminals on the battery are brass inserts, and there are no external and comparatively fragile vent paths such as are incorporated in the earlier model Y. The negative terminal on each cell is identified by a small pillar beside the screw hole.

Older models are usually just as reliable as the model R; the most common problem occurring with age (after abraded corners) being acid leak from the top beside the terminals. Once acid has seeped between the pitch and the lid, it is very difficult to stop. Pitch will only form an efficient seal against the hard rubber if all traces of the acid are removed first. Possibly the best way to do this is to use a pencil-flame blow-torch (see section 7.5).

The capacity of a battery decreases with age and use, and as old models would originally have had less capacity than modern types, this implies that such batteries would not be expected to give long discharge times now. Despite this I have seen a 17 year old model W, whose owner assured me that it still gave eight hours of light (so the discharge time was probably about 6.5 hours) – this says something for the quality of the battery.

All the Oldham types mentioned above include 2 Amp fuses which are mounted between the cells. These are often replaced with wire by cavers (see section 6).

The Ceag CgL lamp incorporated a fairly standard type of battery which has now been changed to the Exide Triclad battery. This was first used in the Patterson SSI lamp (recognisable by the jack-plug charging socket on the battery cover), and is now widely used in the Ceag CgL2 lamp.

This battery is outwardly similar to the Oldham batteries, the most obvious difference (other than the name on the front) being the filler plug and venting system. The plug itself is larger on the Exide battery, and the gas vents come out under the Plug as the holes in the plug form part of the venting system.

The other external difference is the general configuration of the battery top. The fuse is in effect in one of the leads from the battery, and the inter-cell connection is an integral part of the battery. An important difference from the Oldham types is the polarity of the terminals. On Oldham batteries, positive is on the right; on Exide batteries, positive is on the left when viewed from the front.

Exide batteries have extremely sensible extra thick bottom corners – an important point for cavers whose batteries are exposed to a great deal of very abrasive wear.

The internal construction of the Exide battery is similar to the Oldham types, the main difference being the multiple separators and envelopes. Unfortunately the sectional view, which shows this well, is no longer available.

The Oldham model T battery (see Fig. 7) rectifies virtually all the disadvantages inherent in earlier models, and seems to represent a major breakthrough in battery design.

The main innovations are:

Polycarbonate case and one piece lid;

Integrally moulded loops for belts;

Transparent panels on each cell which allow immediate inspection of electrolyte level, and include dual function apertures for topping up and venting.

These points make for a very easily maintained battery, which should stand up well to caving conditions.

All standard covers fit these batteries, and as is normal with Oldham types, the fuse is mounted between the cells.

All types of batteries have similar electrical characteristics, and may be charged on the same equipment. They are in effect fully interchangeable.

4. HEADSETS

4.1 General

The headsets used on modern lead-acid lamps incorporate without exception the Oldham type charging contacts and switch. However, some cavers use headsets 'cannibalised' from old alkali lamps, so I shall briefly describe some of these first.

The simplest and hence most robust type is the one bulb headset such as the old Edison. This is small and light, if equipped with a plastic bezel. It does not have the (mainly psychological) advantage of a reserve bulb, and no switch is incorporated. If a low profile switch is mounted on to the battery cover (a slider switch is ideal), the headset can be very useful as it is so small.

There are many two bulb types designed for alkali lamps. These include both Nife and Ceag headsets. Many Nife types have the unique one-piece perspex cover. This when new can allow a higher light output (Roberts: 1958) but becomes quickly scratched in use. The Ceag type has a very robust switch worked by a cam action, but is deeper and heavier than the modern headsets designed for lead-acid lamps. However, this type does have a very deep parabolic reflector that can be polished to give a superb spot beam (see the next section).

All the types mentioned so far do not include charging contacts, and so either the battery cover or the headset must be dismantled in order to charge the battery. All modern headsets include contacts and a switch which allow the battery to be charged through the headset without dismantling. The purpose of the switch is to avoid the possibility of the battery being accidentally short-circuited while underground in a mine (which would cause dangerous sparks); however a normal charging rack may be used to draw current from the battery if desired.

Most Oldham headsets in use are type 'G' – these have proven their reliability over many years. In addition to the charging switch, there is an internal four-way wiper switch for selecting either the main bulb or the pilot bulb, with two "off" positions. This is the most vulnerable part of the headset, should water be allowed to seep in. Modern type 'G' headsets, usually recognisable by the yellow bezel ring, have a one-piece plastic reflector and main bulb holder. The purpose of this is to allow easy focussing of the bulb, since more and more spot reflectors are being used. Unfortunately the wire completing the lamp circuit is easily broken by careless handling, and also the coating on the reflectors is apparently very susceptible to damp-so especial care must be taken with the headset seals.

Very similar to the Oldham headset is the Ceag model. This is recognisable by the cross-bar that carries both bulbs, and the stainless steel main bulb-holder. The pilot bulb for these is a small 'pea' bulb, so the side hole in the reflector must be enlarged if the more commonly available 0.5 amp bulb is to be used. The switch is a knife blade type which is stronger, and probably more reliable, than the Oldham switch – however an uncommonly small allen key is required to dismantle the switch for maintenance.

The clip at the back of all headsets is angled at 30° to the glass, and this point should be remembered when brackets are being fixed to non-standard helmets (brackets should be vertical).

The toughened glass front should always be kept as clean as possible – especially during muddy trips – to ensure maximum light transmission. It is estimated that a 'typical' thin smear of mud will reduce the light output by about 25%, and will also destroy the shape of a spot beam.

4.2 Reflectors

The subject of reflectors has always been a point of controversy; some cavers swear by spot reflectors, and others by diffuse. Whereas this is partly a matter of personal opinion, there are certainly strong and logical arguments for both types.

Diffuse reflectors give a broad beam spread over a wide area near the wearer. They also carry less chance of dazzle should the light be accidentally directed into the face of another caver (Roberts: 1958). Some users of diffuse reflectors claim that using a spot reflector gives them headaches; if this is so then they must obviously use a diffuse reflector. A diffuse beam will also be particularly useful in low or constricted passages where it may be necessary to bend one's head away from the desired field of view.

A spot reflector can take a bit of getting used to as more head movements are required. The main advantage is in walking-sized passages or chambers, especially those with boulder-strewn floors, as one can look further ahead with a spot beam, and relief on the floor shows up better when the spot is moved across it. Also, of course, one can better appreciate the magnitude of large passages with a far reaching spot beam.

The only conclusion that can be drawn from the above is that possibly one should choose a reflector according to the trip attempted: for instance a spot beam is ideal for most of Ogor Ffynnon Ddu II, but for Penyghent Pot a diffuse reflector might be the better choice.

The deep reflectors used in the Old Ceag alkali type headset are claimed by some to give a very good spot beam. To achieve this, the reflector must be polished – if this is done (and this applied to polishing all types of reflector) precautions must be taken to inhibit tarnishing which could result in a 15% drop in light output (Roberts: 1958). Polishing is best carried out on a lathe, or by fixing the reflector to an electric drill using a sandpaper disc holder.

Modern reflectors should normally never be polished, as they have an extremely efficient vacuum deposited surface which is coated with a special protective varnish. Further, some reflectors are not aluminium all through. The latest types, as described in the last section, are based on plastic; others are based on brass.

If a reflector should get mud or grease on its surface, water and soap (not detergent) may be used to remove the dirt. A badly scratched or dirty glass will also affect the light output and beam shape of a lamp.

With all reflectors, changing the position of the bulb will change the light distribution pattern. The best position may be found by trial and error by moving the bulb in or out until the most satisfactory result is obtained. With parabolic spot reflectors, the bulb filament should be at the focus of the reflector.

A comprehensive treatment of the distribution patterns given by different reflectors is included in 'Underground Lighting' (Roberts: 1958). Problems of glare are also discussed there, and elsewhere (Neill & Bell: 1972).

4.3 Bulbs

Main bulbs for use underground in coal mines are covered by BS535 : 1973, and cavers should always use bulbs that conform to these specifications. All such bulbs are now Krypton-filled, which means

that about 17% more light is obtained at a given wattage, than with Argon-filled types. The reason for this is that Krypton has a higher density and a lower specific heat than Argon, so higher filament temperatures can be used which in turn leads to higher efficiency.

Bulbs are normally rated at 4 volts, 1 amp; and occasionally at 3.6 volts or 0.9 amps. The mean discharge voltage of a lead-acid battery is typically 3.8 volts, hence a 4 volt bulb is being underrun for most of the discharge period, with a mean drop in the light output of about 12% (Roberts: 1958; Cotton: 1955). There is therefore some argument for using bulbs rated at 3.6 volts if any are obtainable. As the bulb is then being overrun by 7% on average, improved light output is obtained at the expense of a slightly higher current drain and reduced life (being about 60% of normal).

It is informative to consider the performance of a standard 4 volt 1 amp bulb as the voltage drops from 4 volts, as occurs at the end of the discharge period. Some voltages are tabulated below for a typical bulb.

4 volts:	1.00 amps:	Normal full brightness.
3.4 volts:	0.94 amps:	Brightness first noticeably dimmer than normal.
2.5 volts:	0.80 amps:	Brightness equivalent to normal pilot bulb at full voltage.
1.8 volts:	0.70 amps:	Light weak but just usable.
1.2 volts:	0.60 amps:	Light no longer usable.

From this table it may be deduced that there is no great saving to be made by switching over to the pilot bulb once the main bulb becomes dim, since the pilot bulb would then be dimmer still, and possibly unusable. It is far better to switch the lamp off for 30 minutes or so, and then perhaps use pilot bulb. (see section 3.2).

The specification for the life-span of main bulbs is laid down to be 200 hours continuous (BS535: 1973). In practice, bulb life has been found to vary between 400 and 4500 hours of normal use (Roberts: 1958; BS535: 1973). It therefore seems most improbable that a bulb would last for less than 400 hours, so the careful caver could virtually eliminate the possibility of bulb failure underground by carrying out a routine replacement after 400 or 500 hours.

Bulb failures are caused mainly by mechanical or normal end-of-life breakage of the filament. Occasionally with older bulbs the cement holding the cap to the glass part disintegrates. If this occurs, the bulb is best replaced since it must be fairly old. Barnard (1936) states that filaments are strongest when hot; a point to be borne in mind when headsets are being banged around in transit.

Modern bulbs have a filament temperature of over 2800°C, and do not give a pure white light, the colour being similar to that of the common household mains bulb. The total light output is typically 40 lumens, which may be considered to be about three candle-power. The reader is referred to 'Underground Lighting' (Roberts: 1958) for a full discussion on photometry as applied to miners' cap lamps.

Most of the above also applies to pilot bulbs, which are rated at 4 volts, 0.46 amps (for Oldham lamps); or 4 volts, 0.3 amps (for Ceag lamps). If a lamp is used solely on pilot bulb, the increased efficiency due to the lower discharge rate would result in an increase in the discharge time of about 2.2 or 3.5 times respectively, when compared with the normal main bulb discharge time. This might be relevant if a lamp is being used for continuous low-level illumination — at an underground camp-site, for example.

Unless damaged, pilot bulbs should last indefinitely if subjected to normal occasional use.

5. THE CABLE AND BATTERY COVER

Cables are almost without exception spirally wound short lay types with a central textile cord to reduce stresses in the wire cores themselves. The whole is enclosed in a close fitting sheath of polychloroprene which fills all the gaps between the inner cores (BS4945: 1973). The cores have a low resistance (less than 0.03 ohms per metre), which means that power wastage in the cable is about 1% of the power developed by the battery during discharge.

The identification colours for the cores are:

Positive:	Brown	(Red on old cables)
Negative:	Blue	(Black on old cables)

The most common cause of damage to the cable occurs when it is used to pick the lamp up. This can cause internal stresses close to the battery which may lead to an increase in resistance or an open circuit, especially in older cables where the centre cord might have been broken or weakened. Also, if the cable grip is defective, the wires could be pulled off the battery terminals. The best way to test the resistance of a cable is to switch the lamp on, and then to measure the voltage across each of the two cores. Neither should exceed 0.1 volts, and should be less than 0.05 volts.

The length of cables is usually about 1.3 metres, but the individual caver might prefer a longer or shorter cable. Metal clips for attaching cables to the rear of helmets should be carefully inspected to ensure that they cannot damage the cable. In general, nylon or similar cord is preferable to a metal clip, since high stresses may result whenever the cable is held at a sharp angle to the clip, as may occur while crawling.

Battery covers are all very similar in design and are interchangeable between batteries of different makes. They are made of stainless steel, and incorporate some form of cable grip, and a grommet where the cable leaves the cover. Covers are held on by a simple locking device with a special screw that is sealed with wax when the lamp is used in mines. This seal is usually removed, and a normal slot cut in the screw when the lamp is used for caving (see section 6.).

The Oldham cover has a very much better cable grip than the Ceag type, at the expense of increased height. In addition, since the cable leaves the cover in the middle, the cable is far more protected against abrasion than with other types of cover.

6. MODIFICATIONS

Some possible modifications are described in this section. They are lettered, and interspersed with comments.

a) The standard miners' cap lamp has two locks on it in order to conform to BS4945 and the NCB safety requirements. These locks are wax filled, and exist to prevent unauthorised tampering while underground. For covers these precautions are not required, and indeed it may be desirable to be able to dismantle the headset or battery cover while in use, for inspection, or to effect a temporary repair. The first two modifications which are carried out almost without exception are therefore:

Cut through or remove the headset bezel locking pin.

Remove wax from battery cover lock, and either replace the special screw with a normal one, or cut a slot in the original screw, so it can be removed with a normal screwdriver.

b) B. Joplin (Private communication; 1974) has pointed out that if it is necessary to remove a battery cover underground, it is considerably simpler if a wing-nut arrangement is used:

Cut screw guard off cover lock, and either replace screw with a commercial wing-nut and bolt, or convert the existing screw by brazing a short piece of rod to its head.

c) It is very common practice to replace the fuse with ordinary wire (or omit it entirely in the case of Exide batteries). The reason for this is that short circuits are often only temporary, and if such an event should occur underground, the fuse would blow and one would be left totally without light. The danger is the risk of damage to the battery or the possibility of a great deal of heat being generated by a short circuit. An alternative to using plain wire is to instal a low value resistor together with a low voltage bulb. The effect of this is to afford a measure of protection against short circuits (and also obviates the need for a ballast resistor during charging — see section 7.3). However, 1/13th of power is wasted, and light output is reduced by 10%, compared with the normal system using a 4 volt main bulb. It is up to the individual to decide whether he values light (and by implication, safety) or his battery most! It is suggested that if a lamp is properly maintained, there is very little chance of there being a short circuit, and therefore it is generally safe to replace the fuse with plain wire. The modifications discussed are therefore:

Replace fuse with normal wire; OR Replace fuse with a 0.33 ohm resistor (3 watt, wirewound), AND replace bulb with a 3.6 volt 1 amp type.

d) If this latter method of fuse replacement is not used, a 3.6 volt bulb can be used anyway to give a greater light output, as described in section 4.3. i.e. replace main bulb with one rated at 3.6 volts at 1 amp.

e) Some older headsets have a small, rounded switch-knob which can be very difficult to grasp when muddy or when one's hands are cold. A cure for this is: stick a toothpaste-tube cap onto the switch-knob with an epoxy resin glue. (This can make the switch more likely to be turned on or off accidentally.)

f) Some users advocate totally filling the battery cover with wax or pitch. This makes it difficult to inspect contacts, and could cause stress points in the wires if inexpertly carried out. It also makes replacement of batteries or cables difficult. The advantage is that it will totally inhibit corrosion and shorting inside the battery cover: fill battery cover with soft wax or pitch.

g) A much used battery will often be found to have worn corners, especially the Oldham type R which has a comparatively soft casing. This will eventually lead to an acid leak, and so it is necessary to strengthen the corners in some way should such wear become apparent. Probably the best way to do this is to use a metal mesh, like an old loudspeaker grille, or alternatively aluminium mesh as used for car body repairs. A stainless steel cover can also be used: coat bottom of battery with a car body-filler, then wrap mesh around corners. Clamp or weight until set.

h) For long trips of over ten hours where it is desirable to use two batteries, it is possible to use the alkali lamp system — that is, use one headset, cable, and battery cover; and one 'blank' cover to protect the spare battery. Contacts inside the 'live' battery cover can be made from car contact breaker springs (B. Joplin: 1974, Private communication), and the blank cover can be used to carry a spare bulk. The author has been assured that this system works well in practice, with no contact problems. i.e.:

Convert battery cover to make contacts with battery by means of springs — this allows easy movement of cover from one battery to another.

The reader may decide to carry out some of the above modifications, or perhaps some of his own. However, whenever any changes are made to a standard battery, possible disadvantages and dangers should always be carefully evaluated.

7. CARE AND MAINTENANCE

7.1 Electrical abuse. Summary

Lead-acid lamps are not as tolerant of electrical abuse as some others utilising different types of battery. The most common problem, sulphation, is mainly caused by storing batteries when they are not fully charged. This leads to the forming of a hard crust of lead sulphate on the negative plates as the crystal structure of the lead sulphate changes. This effectively reduces the porosity of the plates, and hence the capacity is also reduced. (see section 3.3).

Overcharging a battery will also eventually lead to damage, as will using too high a current while charging or discharging.

Using an incorrect type of bulb will always be inefficient, and could damage the battery if too high a current is taken by the bulb (see section 4.3).

7.2 Mechanical Abuse. Summary

One of the causes of cable failure, especially in older lamps, is using the cable to pick the battery up. Even if the cable is known to be well anchored, this practice can cause failure as undue strain is put on the wire cores. This can eventually lead to a total breakage, or the breakage of just a few strands which increases the resistance of the cable.

Care should always be taken to avoid banging headsets on the ground etc. when in transit, as, despite their excellent design and great strength, repeated shocks could lead to failure. The bezel is especially prone to damage. A tidy way of safe-guarding the headset is to tie up the cable in a loose overhand knot.

On some older batteries, the screw threads on the top are in lead which is soft. If care is not taken, the threads are easily stripped if the screws are overtightened.

On many batteries the cover over the topping up holes is brittle. It can easily be cracked, and ideally the proper tool should be used to remove or replace the cover.

It is sensible to keep batteries, and indeed the entire lamp, clean. This allows easy inspection for damage or wear.

7.3 Charging

(see also section 3.4).

In order to achieve satisfactory performance, lead-acid batteries must be charged correctly. If not fully charged, the lamp could fail unexpectedly early which might be dangerous on an extended trip underground. If repeatedly overcharged, damage will occur to the plates.

There are many methods of charging lead-acid batteries, of varying complexity (Smith: 1972, Neill: 1965, Manoharan: 1972), some of which require relatively complex electronics. These include such methods as gas, float, and temperature-controlled charging.

In Britain, lead-acid lamps were charged by constant current methods until the mid 1930s. This was manually controlled, with frequent adjustment of voltage being required to maintain the constant current. This was often skimped or incorrectly carried out, with the result that lead-acid lamps acquired an undeserved reputation for unreliability. Gradually, first in the United States and then in Britain, the modified constant potential method — now used universally — became accepted.

To recap, with this method a voltage, typically 5 volts, is applied across each battery through a ballast resistor. Originally, this resistor used to be incorporated in the headset cable, but obviously this was inefficient during discharge, and so nowadays it is included in the charging equipment instead, usually in an ammeter. This ballast serves to limit the current throughout the charge, which is initially approximately 1.8 amps if the ballast resistor is 0.33 ohms and the battery has been discharged normally. As charging progresses, E (the battery open-circuit voltage) will rise slowly (see Fig. 6a) and so the current will fall. When the battery is fully charged, the voltage will approach 5 volts, and the current will have dropped to about 100 milliamps.

This method is undoubtedly the best for general use by cavers, since it is almost foolproof — a necessity — and cannot lead to overcharging if any lamps on charge are taken off within a week.

It is recommended that, wherever possible, the Oldham charging system should be used, where the battery is charged via a special rack and the contacts on the headset. Not only is this vastly more convenient than removing the battery cover etc., but it also makes incorrect connections an impossibility.

Some people charge several lamps in series, with, for example, 30 volts being applied across six batteries. A moment's thought will show that this can lead to serious overcharging: suppose five batteries need full charging, and the other is nearly fully charged. Initially, more than 1 amp will flow through all six batteries, and will continue to do so for some hours. This of course will overcharge the battery that was initially well charged. Therefore, lamps should not be charged in series unless they have had the same amount of use, and all the batteries are known to have similar characteristics. Even then the method should be used with care.

The 'ideal' charger is therefore a 5 volt supply which has the charging racks and ballast resistors (one resistor to each rack) connected in parallel across it. The ballast resistors should be about a third of an ohm, and if ex-equipment (or new) Oldham or Ceag ammeters are available, so much the better. These resistors also serve to limit any currents that might flow should lamps be on the racks when the charger is not switched on.

The 5 volt supply should be controlled in such a way that the voltage cannot rise above 5.05 volts; if this is the case then lamps may be left on the charging racks for several days at least. Ideally the voltage should be electronically regulated, especially if a large number of lamps are to be charged. It is realised that for reasons of economy this may not always be possible, and so a watch may need to be kept on the charger output voltage. Circuits for constant voltage regulators of high current ratings may be found in many standard electronics reference books, since 5 volt power supplies are often needed for modern electronic equipment.

As with most engineering problems, a compromise has to be made building an expensive 'super-charger' to eke out every day of life from ones batteries; and using a cheaper system which could mean more frequent replacement of batteries or longer charging times.

During an emergency of some kind, it may be necessary to charge lamps as fast as is practicable without causing permanent damage. To achieve this, a charge tapering from 2.5 amps to 1 amp can be used (Neill: 1974; Private communication). This will recharge a fully discharged battery in 5 to 6 hours, and the battery will be 80% charged in about 4.5 hours. This taper charge can easily be carried out using the normal charging arrangement but with a supplied voltage of 5.4 volts. With this method, the lamp must be taken off charge as soon as its voltage has risen to 5 volts. Failure to do this will result in overcharging.

If a lamp is not expected to be used for some time, it should be stored away from high temperatures, and should be given a discharge/charge cycle at least once a month. The battery should always be fully charged before storage.

Finally, it must be remembered that all mains-run charging equipment should be fused and adequately earthed – as it is all too easy for a charger being used by cavers to become damp.

7.4 Maintenance Checks

Using an unreliable lamp is as irresponsible and dangerous as using an unsafe ladder or rope, and so the same care should be taken over the maintenance of lamps as over the maintenance of other equipment. The chances of a lamp failing in normal use can be kept down to negligible proportions by using common sense and a logical approach to maintenance.

The areas where most faults occur are indicated in Fig. 8. It is suggested that a scheme of maintenance be followed which will detect all of these potential faults. For those who like a set scheme, the following two part method is suggested – the first part, of simple checks, can be quickly carried out between trips, and the second more exhaustive part could be carried out after every 25 trips (or more often if the lamp is not used regularly). Some possible remedies for any faults that might be found are described in the next section.

Between trips:

- A Check both bulbs light.
- B Check both bulbs switch reliably.
- C Examine battery case for holes and cracks.
- D Check battery for signs of acid or corrosion.
- E Check cable is gripped securely at both ends and is not damaged.
- F Clean headset glass.
- G Check for water inside headset.

After 25 trips:

- H Check electrolyte level. (Preferably more often.)
- I Open headset, and check seals.
- J Open headset, and check condition of cable in headset.
- K Open headset, and check bulb contacts, metal strips, and switch.
- L Check charging switch.
- M Open battery cover, and check inside for signs of corrosion.
- N Open battery cover, and check cable, grip, and wires to terminals.
- O Open battery cover, check terminals for good contacts.
- P Charge battery, and test discharge time – it is not a bad idea to keep a record of all such tests for each battery owned.

Where a set of lamps is owned by a club rather than by individuals, each caver who uses a lamp should remember that it is his (or her) responsibility to check that the lamp being used appears to be in good condition. Also, should any fault appear during use, it should be reported to whoever maintains the lamps; and the lamp should be clearly labelled to ensure that it is not accidentally used before the fault is corrected.

7.5 Repairs

This section describes some remedies for the faults listed in section 7.4. It is not intended to be a detailed maintenance manual, but rather a general guide.

- A If only one bulb fails to light, either the bulb is faulty, or more probably the switch is corroded or broken. Replace bulb or faulty part. If neither bulb lights, first check switch and contacts inside the headset. If no fault is obvious, carry out a full maintenance check, as a more serious fault must exist.
- B If switch is unreliable, dismantle and clean it. If no improvement, replace contacts.
- C Battery may have to be replaced, but car body filler may do the trick. First turn the battery so hole is uppermost, wash and leave for 24 hours. Then remove all remaining traces of acid with sandpaper or a small blowtorch.
- D If acid comes from top of battery, pitch can be used to reseal the leak, after all traces of acid have been removed – ideally with a small blowtorch. If the acid comes from the vents, the cells have probably been over topped-up – check. If the acid comes from the case of the battery, treat as in C. If acid comes from topping-up seal, smear lightly with vaseline – note that care must be taken with Exide batteries not to block the holes in the plug, since they form part of the venting system.
- E If loose at headset end, tighten grip-nut. If loose at battery cover, the gripping device is probably broken and needs replacing. If the cable is damaged, replace, or cut off damaged area if near end and the resultant shortened length can be tolerated.
- F If glass is badly scratched, light will be over-diffused. Replace.

- G Dismantle headset. Check switch seal, cable seal, gasket ring. Vaseline on the latter may help. Replace faulty seals. Clean and dry every part of the headset before reassembly.
- H With all types of batteries, the electrolyte should just cover the plates. Any higher and the non-spill system will not work correctly; much lower and eventually the capacity of the battery will be reduced. If a great deal of topping up is needed, check for leaks or a fault in the battery charger causing overcharging.
- I Replace if damaged. See also G.
- J As E.
- K If not obviously in good condition; dismantle and clean all parts. Replace any suspect parts. All parts should be lightly smeared with vaseline before reassembly.
- L Dismantle switch and clean parts. If any seem very worn, replace. Do not apply any lubricant or grease, as this can trap grit and form an abrasive paste.
- M Acid corrosion implies acid leak. Clean affected parts, and replace any severely damaged (including cable). Repair acid leak – see D.
- N Cable should be checked for short circuit, open circuit, or high resistance due to corrosion. If any of these are found, it is best to replace cable. If grip is inefficient, it will probably need to be replaced.
- O All terminals should be clean and virtually free from corrosion. Undo all screws, clean contact areas, smear with vaseline and replace. Excessive corrosion is probably caused by an acid leak. See M.
- P Charge battery fully (see section 7.3). Allow to stand for about an hour, then switch on main bulb. Leave on continuously and time until voltage across battery falls to 3.4 volts. This time is the discharge time of the battery, and should be at least 7 hours. The discharge time will drop with age, but it is possible that sulphation has occurred (see section 3.3). If this is suspected, a reconditioning charge of a third to one half of an amp should be applied for about 30 hours. This will normally result in an increase of discharge time. If it does not, the battery is either damaged beyond repair by severe sulphation or other abuse, or has reached the end of its life. In any case, before a battery is discarded for giving a low discharge time, a reconditioning charge should be tried. The charger being used should also be checked, as if it is faulty, then the battery may not be receiving a full charge.

In many places in the above, replacement of faulty parts is advocated. Where appropriate, suitable home-made replacements can of course be used, though their suitability and safety should always be carefully assessed first.

8. CONCLUSIONS

In the author's opinion, the possibility of lead-acid lamp failure underground is extremely remote if common sense is used, and a few simple rules are adhered to.

The maximum life should be obtained from a lamp if:

- Constant Potential charging with a maximum of 5.05 volts is used;
- The battery is recharged as soon as possible after use;
- The cells are topped-up regularly;
- The cable grips are maintained in good condition;
- The interior of the headset is kept dry.

In an emergency; the following facts could be very useful:

If a battery has been discharged until the light is no longer usable, a surprising amount of light can be obtained by switching off for up to two hours so the battery can 'recuperate'.

An 80% charge can be achieved in about 4.5 hours by using a fast charge tapering from 2.5 towards 1 amp.

It is hoped that the information included in this paper will be useful to many people, and will contribute towards the safety of any speleologist or sportsman using a lead-acid cap lamp underground.

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