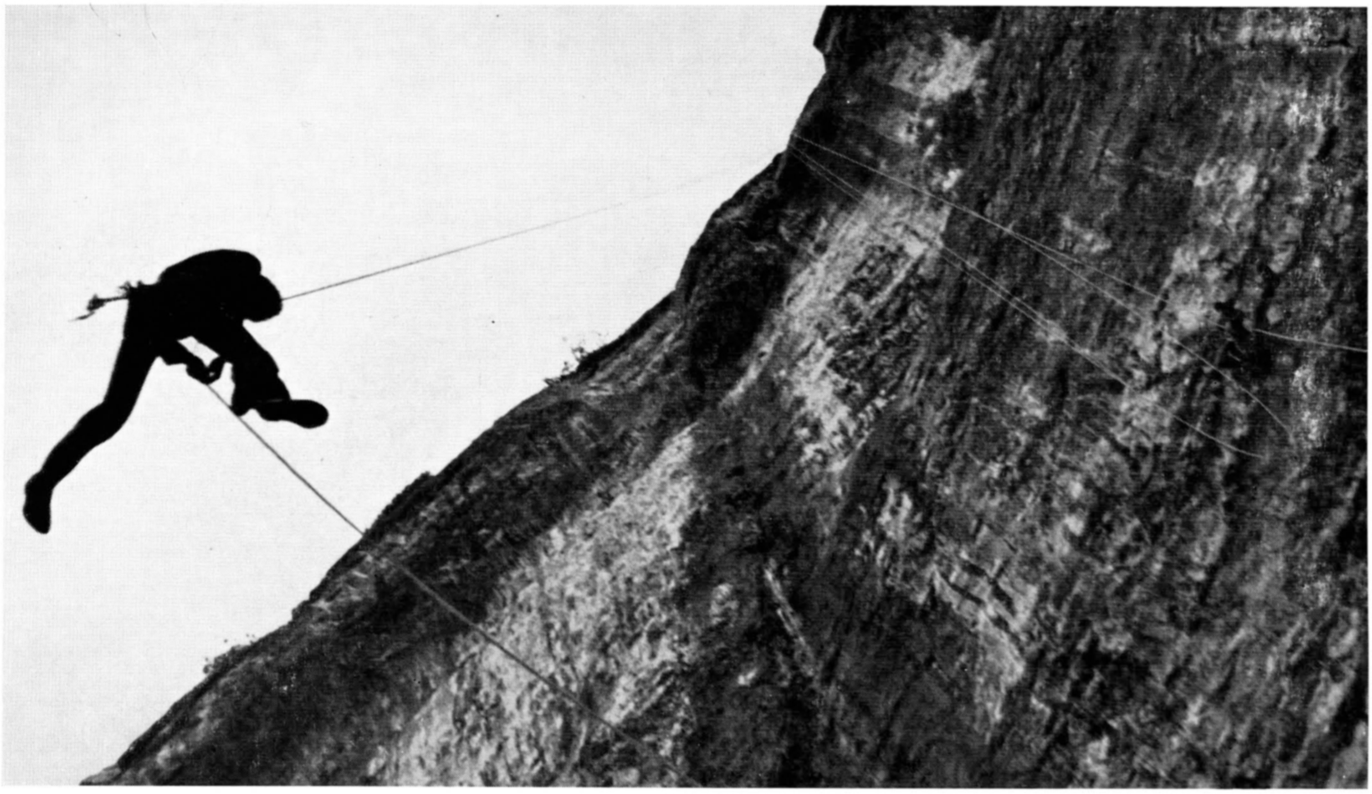
BCRA TRANSACTIONS

BRITISH CAVE RESEARCH ASSOCIATION

Volume 1 Number 4 December 1974



Tests on Ropes

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A very short summary of the principal conclusions should accompany every contribution.

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Bloggs, W., 1999. The speleogenesis of Bloggs Hole. Bulletin X Caving Assoc. Vol. 9, pp. 9-99.

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Cover picture – **Testing ropes at Malham Cove, Yorkshire.**
Photo by Bob Greenwood.

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The British Cave Research Association

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Trans. British Cave Research Association. Vol. 1. No. 4. pp.181-198. December 1974.

THE ROPE IN SINGLE ROPE TECHNIQUE CAVING

by A. J. Eavis

(paper presented at the British Cave Research Association conference in Leeds, September, 1974)

Summary

The detailed results of a series of tests for abrasion resistance, ultimate tensile strength, chemical resistance and stretch on some 20 different ropes are presented and their significance discussed as regards the practical implications of rope selection and usage.

Introduction

The first series of tests resulted from the availability of a large tensile testing machine, the increase in importance of ropes with change to single rope techniques, and a very great interest in self-preservation. The possible importance of the tests became apparent when the second rope tests with a believed new ultimate tensile strength of 2,900 lbs failed at 900 lbs. This emphasizes two points; rope can become very weak and it is very easy to be quoted incorrect figures by ignorant retailers.

Ultimate tensile strength tests were done on many of the club ropes which were mostly plaited polypropylene, as well as knot and knot/carabiner combinations. All the ropes except one failed below the manufacturers' figures and many old ropes failed at less than 50% of quoted values.

At first it was thought these poor results were due to chemical degradation, but careful examination of the ropes suggested external abrasion (see Figs. 1, 2 & 3). This abrasion was well hidden by the rope construction making it particularly dangerous. Dave Brook undertook a microscopic examination of the used, badly abraded ropes. He measured the fibre diameters which are listed in Fig. 4; he also measured and counted grit particles in the rope. Frequency against size graphs are also included in Fig. 4. In the inside of the very dirty plaited rope very few particles have penetrated and their particle size is almost exclusively smaller than the fibre diameter, suggesting that they play only a small part in damaging the rope. In general, microscopic examination revealed very few damaged fibres inside the ropes. Dave also analysed the limestone used later in the abrasion tests: the insoluble residue of 5.4% was all below 5 microns in diameter showing that the hard abrasives were very fine grained (Fig. 5).

New rope was needed for the club and the forthcoming Papua-New Guinea Expedition where Single Rope Techniques would be used exclusively. Purchase of plaited polypropylene ropes similar to those tested and used by the club in the past for lifelining was, in the author's opinion, not justified but what was the alternative? A collection of information was undertaken and details of over fifty possible SRT ropes collected. To help with choosing the replacement for these, guidance was sought in the speleological press. An excellent article by Frank Solari in 1968 was no real help on abrasion resistance and pointed to the need for abrasion tests. Ben Lyon, in his talk at Buxton in 1972, liked nylon and terylene for SRT due to their high melting points and said that he had found that terylene abrades less easily than any other rope. Robert Thrun in his book on prussiking (1971) states that polypropylene fibres are soft which increases frictional wear and also leads to a kind of stress fatigue — this was admittedly applied to prussik loops.

Since none of the speleological literature consulted gave any clear idea of the abrasion resistance of various types of rope when in contact with limestone, it was decided to purchase several different types of likely looking rope and subject them to a series of tests including abrasion tests. Four hundred metres of new rope was bought; two 100 metre lengths of terylene, one 100 metre length of nylon and one 100 metre length of terylene-sheathed polypropylene. In addition, polypropylene ropes already in the club were tested along with several other miscellaneous ropes including Bluewater III kindly donated by Pete Lord. For the final series of tests Ben Lyon donated three lengths of terylene and one of nylon, so in total twelve different new ropes were tested as well as four old ones (see list in Table 1). The abrasion resistance, ultimate tensile strength and several other things were considered. These are all discussed below and are summarized in Fig. 18.

Table 1 — LIST OF ROPES TESTED

Rope Name	*Age*	*Manufacturer*	*Construction*	*Tests on the particular rope mentioned in text*
POLYPROPYLENE				
Hawser 12mm	Nearly New	Unknown	3-strand Hawser	All except for second abrasion
Plaited 12mm	New	West of England Ropes	8-plait	All except for second abrasion
Plaited 12mm (very dirty)	Old	West of England Ropes	8-plait	Abrasion and Ultimate Tensile Strength only.
Plaited 10mm (badly abraded)	Old	West of England	8-plait	Abrasion and Ultimate Tensile Strength only.

FIG 1

Close up of the end of a Plaited Polypropylene Rope which has been taken to pieces showing how surface wear has greatly damaged plaits.

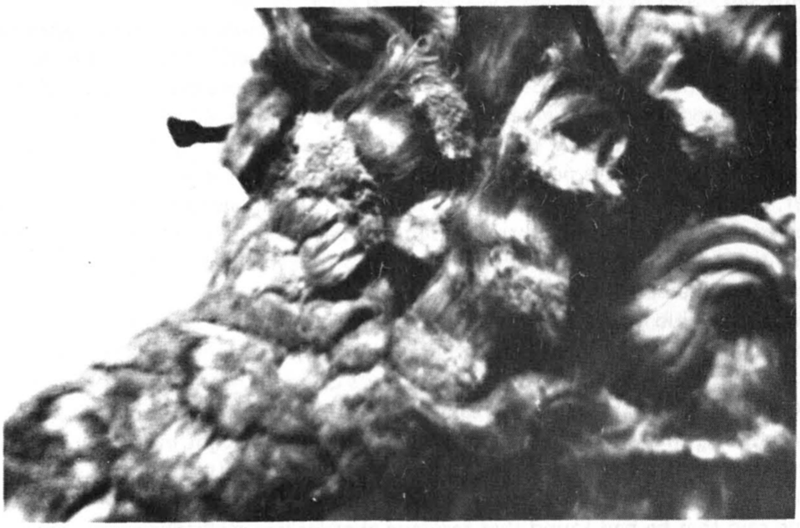


FIG 2

An enlargement of part of Fig 1 showing how some plaits have been virtually abraded through.

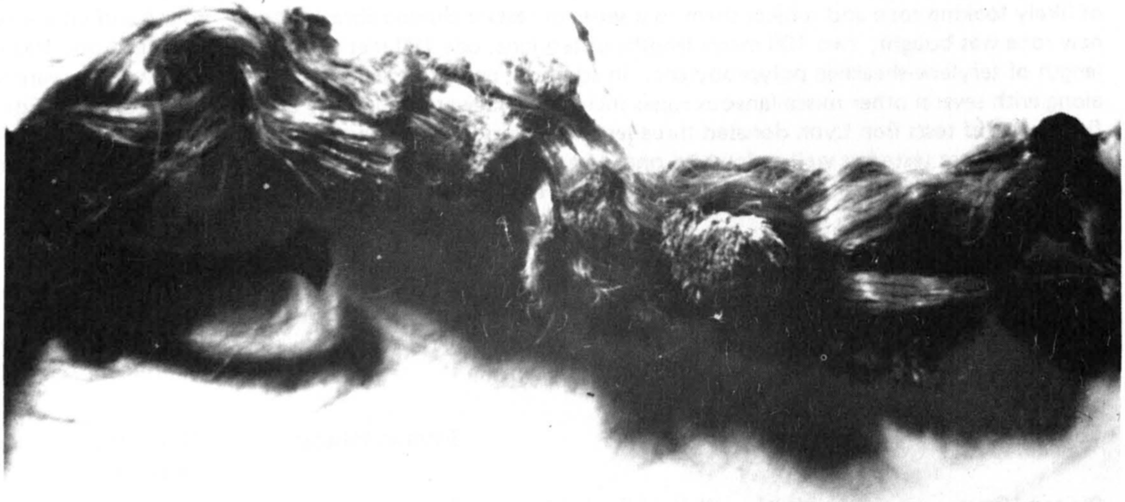


FIG 3 One plait from the above rope showing much damage along its length.

FIG 4

Approx. average fibre diameter as measured under a microscope ;

Plaited polypropylene by W. of E. Ropes	25 microns.
" terylene " " " " "	22 " .
Super Braidline terylene by Bridon	19 " .
" " nylon " "	25 " .
Bluewater III	25 " .

The grit content of an old plaited rope.

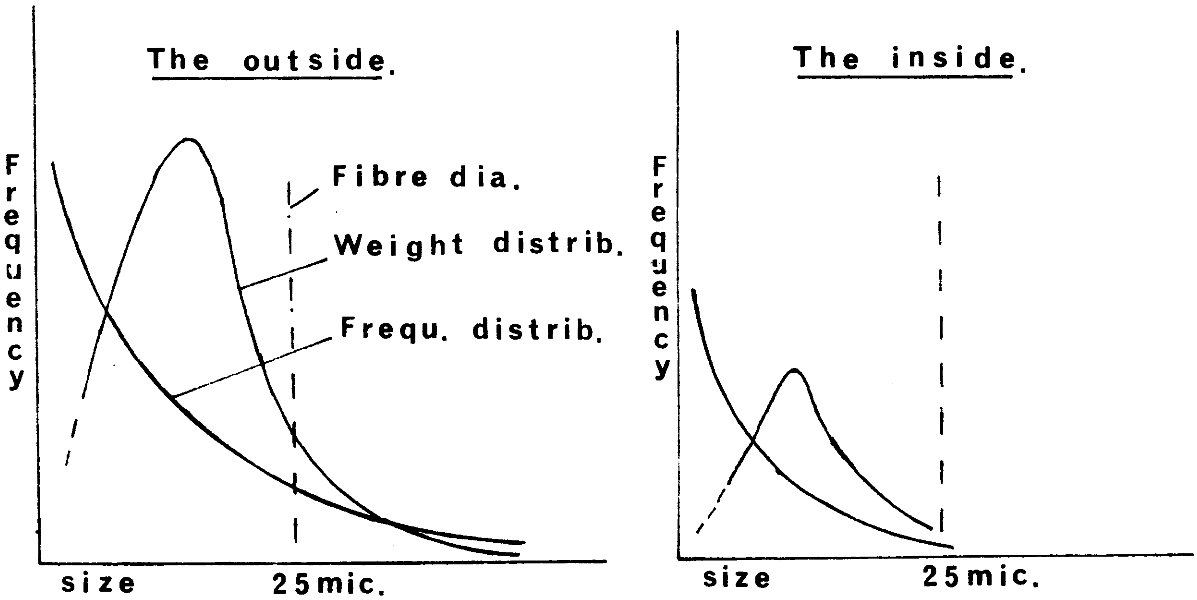
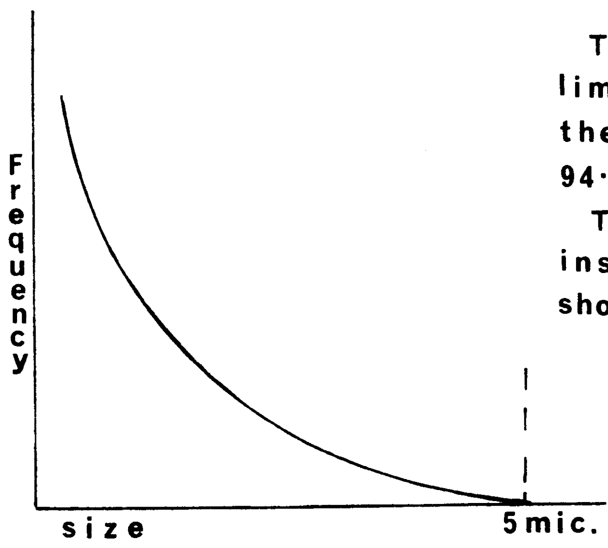


FIG 5



The analysis of the limestone block used in the abrasion tests gave 94·6 percent calcium carb.

The distribution of the insoluble particles is shown left.

Table 1 — Continued

Rope Name	*Age*	*Manufacturer*	*Construction*	*Tests on the particular rope mentioned in text*
TERYLENE				
Braidline Super Polyester 10mm	New	Marina Yacht Ropes	Plaited sheath and plaited core	All
Matt Plaited 10mm	New Ro	West of England Ropes	Plaited sheath and plaited core	All except for second abrasion
Terylene/Polyester 16-plait matt finish 10mm	New	Marlow Ropes	16-plait outer sheath matt, inner sheath 8-plait continuous fibres, straight core	All except for first abrasion
Terylene/Polyester 16-plait matt finish 12mm	New	Marlow Ropes	16-plait outer matt sheath, 8-plait inner sheath continuous fibres, straight core	All except first abrasion
Terylene/Polyester 8-plait Pre-stretched 10mm	New	Marlow Ropes	8-plait sheath with single fibre bundle core	All except for first abrasion
NYLON				
Dynaflex Kernmantel 9mm	New	Distributed by Bridon Fibres and Plastics	Kernmantel	No test which involved destruction
Blue Water II 12mm Polypropylene/ Terylene	Unknown	Blue Water Ltd.	Kernmantel with very tight sheath and less resilient fibres than III	Tests done but not mentioned in text
Blue Water III 12mm	Almost New	To be sold by Ben Lyon, Whernside Manor	Kernmantel with very tight sheath and resilient fibres	All except for second abrasion
Viking Log-Line 13mm	New	British Ropes (Bridon)	8-plait with single fibre bundle core	All except for first abrasion
Viking Log-Line 13mm	Various	British Ropes (Bridon)	8-plait with single fibre bundle core	Some abrasion and some Ultimate Tensile Strength
Braidline Super Nylon 10mm	New	Marina Yacht Ropes (Bridon)	Plaited sheath and plaited core	All
Old Kernmantel 10mm	Unknown	Unknown — found in car park	Kernmantel	Abrasion and Ultimate Tensile Strength
Hawser Nylon approx 10mm	Unknown	Unknown — found in France	3-strand	Ultimate Tensile Strength
POLYPROPYLENE/TERYLENE MIXTURE				
Braidline Marina 10mm	New	Marina Yacht Ropes (Bridon)	Plaited Terylene sheath and plaited Polypropylene core	All

N.B. All ropes are shiny, continuous fibres where not mentioned otherwise. Terylene = Polyester.

Manufacturers' Addresses

Marina Yacht Ropes, Dynaflex and Viking by:—
Bridon Fibres and Plastics,
Condereum House,
171 West Road,
Newcastle-upon-Tyne.
NE99 1AE

Marlow Yacht ropes by:—
Marlow Ropes Ltd.,
Marlow House,
Hailey Road, Thamesmead,
Erith, Kent. DA18 4AL.

West of England ropes by:–	G.H. Smith (Cordage) Ltd., Yeovil, Somerset.
Blue Water by:–	Bill Cuddington, 4729 Lumany Drive North West, Huntsville, Alabama, 35810, United States of America.

Melting Point

Frank Solari gave the melting point of nylon as 250°C, terylene 260°C and polypropylene as 165°C: for the sake of the table (Fig. 18) mixture ropes have been assigned melting points midway between the component fibres. Since all descenders get hot the higher the rope's melting point the better; the fibres do of course start to lose strength considerably below the melting point. The low melting point of polypropylene, in the author's opinion, should exclude it from use in big **dry** abseils. This low melting point also greatly affected the dry abrasion resistance of polypropylene, as will be seen later.

Chemical Resistance

Nylon is badly affected by very dilute acids and terylene by alkalis. Polypropylene is very chemical resistant being affected by only a few common chemicals. William Halliday in his book "American Caves and Caving" lists chemicals liable to damage ropes in general, but probably mainly nylon, as battery acids, vinegar, ketchup, salad dressings, bleaches, household cleaners and a surprising number of other common chemicals. Nylon in particular is degraded by sunlight and all synthetic ropes slowly lose strength with time. Ben Lyon at Buxton said, "If you leave an artificial fibre for eighteen months on the shelf out of sunlight in cool conditions and so on, it may well have lost up to one third of its original strength". The tests mentioned later seem to confirm this for nylon but suggest slower degradation for terylene and polypropylene. Heating any of the ropes for a short period, e.g. a very fast abseil, will result in permanent loss in strength. Ropes must be kept out of direct sunlight, kept cool and away from all sorts of common chemicals and reagents.

Diameters of ropes

What diameter of rope to use is to a very great extent a matter of personal choice. Thick ropes are stronger for the same construction, easier to grasp in the hand and give a slightly higher safety margin, e.g. being cut by falling rocks etc., but they are heavier and might be too large for some ascenders. A compromise between weight and safety has to be found. Most devices will not take a rope larger than 13mm and some are as low as 10mm. The author thinks 10mm is a good optimum for most types of rope fibres and rope constructions. An interesting point is that ropes sold by the manufacturers can be plus or minus at least 1.5mm; the 10mm ropes bought for the purpose of this paper varied between 9mm and 11.5mm. The ropes were measured with a micrometer in various places along a 10 foot length and an average taken. It is possible at least one of them was wrongly labelled by the makers.

Weight

As mentioned above, weight is obviously an important criterion when buying a rope. The weight bears some relation to diameter and rope density taking fibre density into account, is a very rough guide to flexibility. Ten feet lengths of each of the ropes were weighed on a large chemical balance after they had been well dried. They were then soaked in water and re-weighed. Comparing the figures shows the difference in water absorption of the various ropes.

Stretch

Static and dynamic stretch were found as a prerequisite to the abrasion tests. They are also important in their own right if prussiks of 200 feet are not to become 220 feet (20 feet along the floor), and if you do not like a springy rope. For the abrasion tests it had been decided to reproduce the conditions of a rope going over a sharp limestone edge from a very long belay. The amplitude of the reciprocating movement over the edge when a caver ascends will depend on the length of the belay, the stretch of the rope and the method of ascent. The dynamic stretch of each of the ropes to take part in the abrasion tests therefore was found under similar conditions by a simple test at Malham Cove.

Each rope was hung down the central wall which gave a free hang of 240 feet. On each rope at a point level with the ledge 90 feet from the top a marker was attached to the rope. The author then used Gibs ascenders to rope-walk up each rope in turn moving from one rope to another. An observer on the ledge (Fig. 6) measured the static stretch when the weight (author = 150 lbs) was applied, and the dynamic stretch when he ascended at a speed of about one foot a second. The results are all displayed in the table at the end. (Fig. 18)

Abrasion Resistance

A simple rig was now built to synthesise the conditions mentioned above. A metal work lathe with a four-jaw chuck capable of holding a metal bar asymmetrically was the basic driving force. A large block

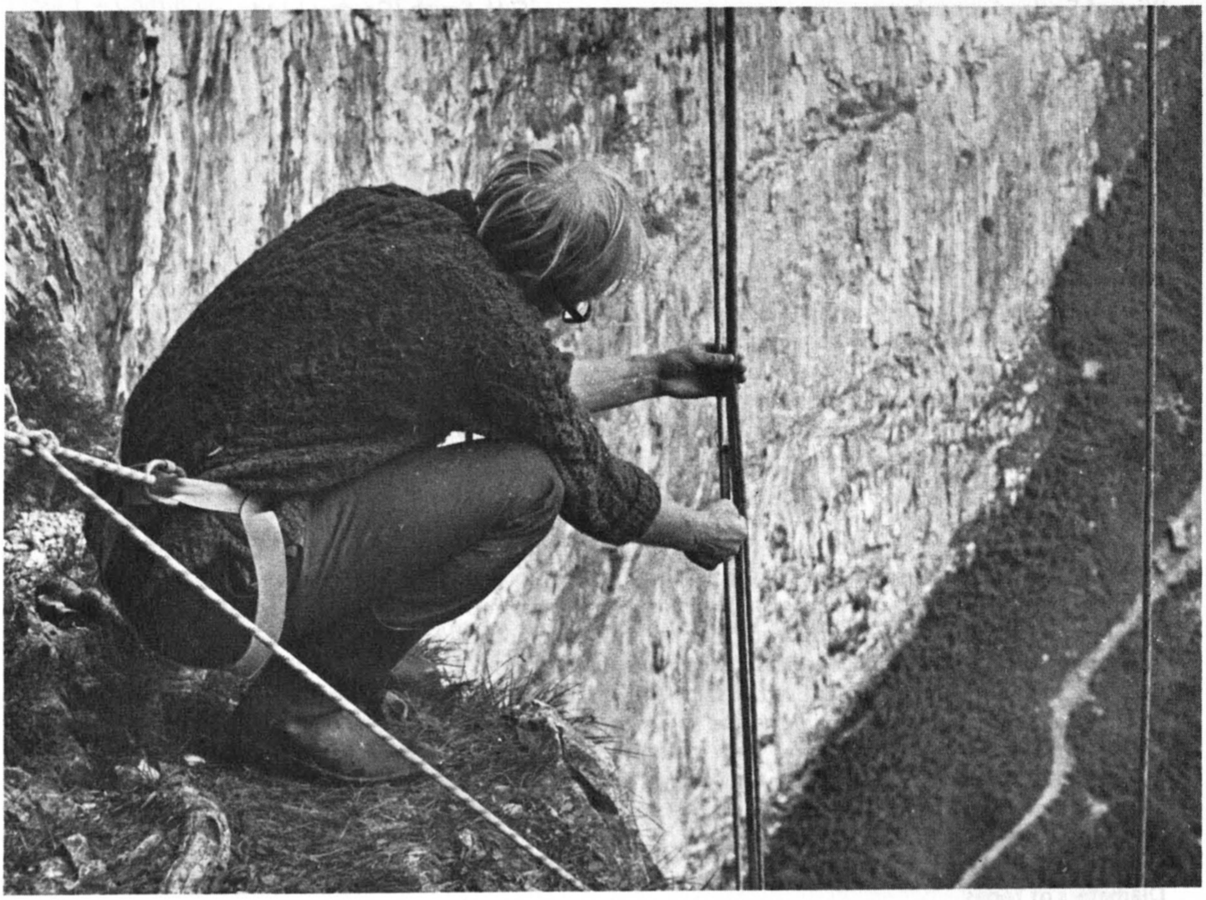


FIG 6

Alf Latham measuring Static and Dynamic stretch on ledge 100 feet from top of Malham Cove.
Photograph by Bob Greenwood.

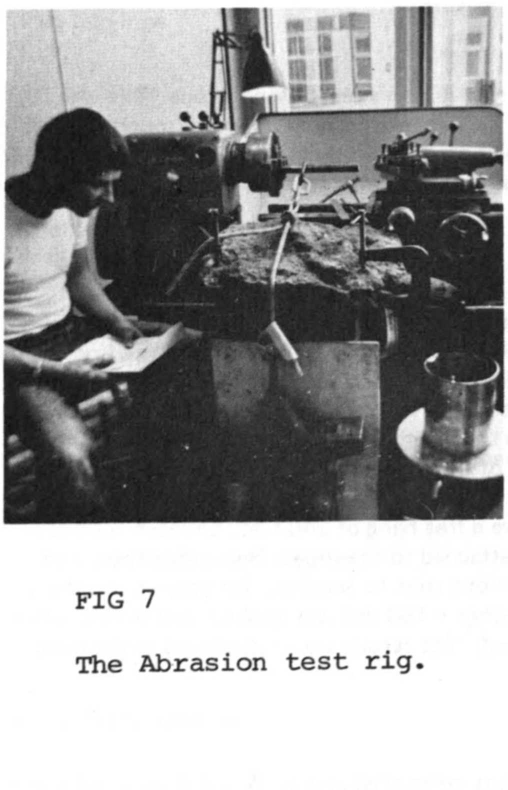


FIG 7

The Abrasion test rig.

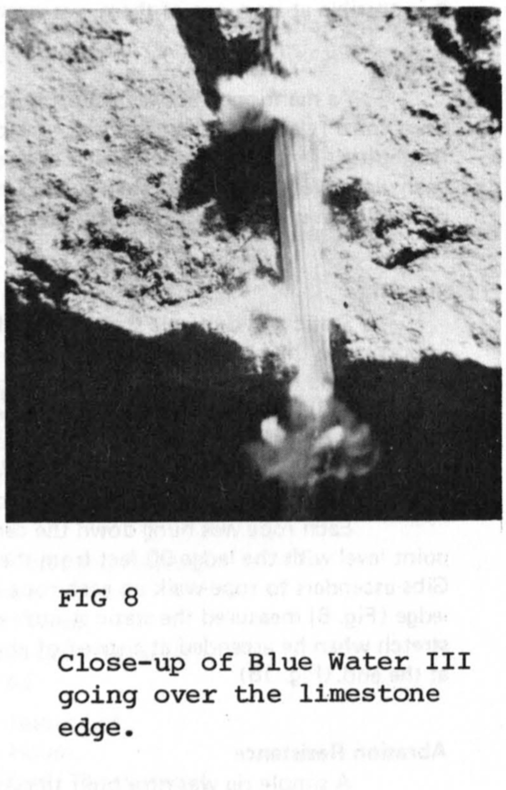


FIG 8

Close-up of Blue Water III going over the limestone edge.

Table 3 Results of the First Series of Abrasion Tests

Groove 1. Weight of 112 lbs. Variable Stroke.

Order of Abrasion Resistance	Rope	Stroke	Time to Failure in minutes	Number of Reciprocations to Failure
	DRY			
1.	Blue Water III 12mm	2"	25.00	1420
2.	Super Braidline Nylon 10mm	3½"	10.20	570
3.	Super Braidline Tery. 10mm	2"	4.87	278
4.	West of England Tery. 10mm	3"	1.63	92
5.	Marina Braidline 10mm	3"	1.58	91
6.	Plaited Polypropylene 12mm	3½"	0.66	38
7.	3-strand Hawser Polyprop.	3½"	0.58	32
	WET			
1.	Blue Water III 12mm	2"	7.75	465
2.	Super Braidline Tery. 10mm	2"	4.62	264
3.	Marina Braidline 10mm	3"	3.88	220
4.	Super Braidline Nylon 10mm	3½"	3.62	206
5.	Plaited Polypropylene 12mm	3½"	2.88	163
6.	West of England Tery. 10mm	3"	2.00	113
7.	3-strand Hawser Polyprop.	3½"	1.66	95

Groove 2. Weight of 168 lbs. Fixed Stroke 3 inches.

Table of abrasion resistance of the test ropes taking groove factor into account. Produced by using Fig. 9.

	DRY			
1.	Super Braidline Nylon 10mm	3"	6.66	380
2.	Blue Water III 12mm	3"	5.35	305
3.	Super Braidline Tery. 10mm	3"	4.91	280
4.	West of England Tery. 10mm	3"	1.14	65
5.	Plaited Polypropylene 12mm	3"	0.96	55
6.	Marina Braidline 10mm	3"	0.58	33
7.	3-strand Hawser Polyprop.	3"	0.53	30
	WET			
1.	Blue Water III 12mm	3"	4.56	260
2.	Super Braidline Nylon 10mm	3"	4.15	237
3.	Marina Braidline 10mm	3"	2.72	155
4.	Super Braidline Tery. 10mm	3"	2.62	149
5.	West of England Tery. 10mm	3"	2.46	140
6.	Plaited Polypropylene	3"	2.46	140
7.	3-strand Hawser Polyprop.	3"	1.49	85

FIG 9 "Groove Factor"

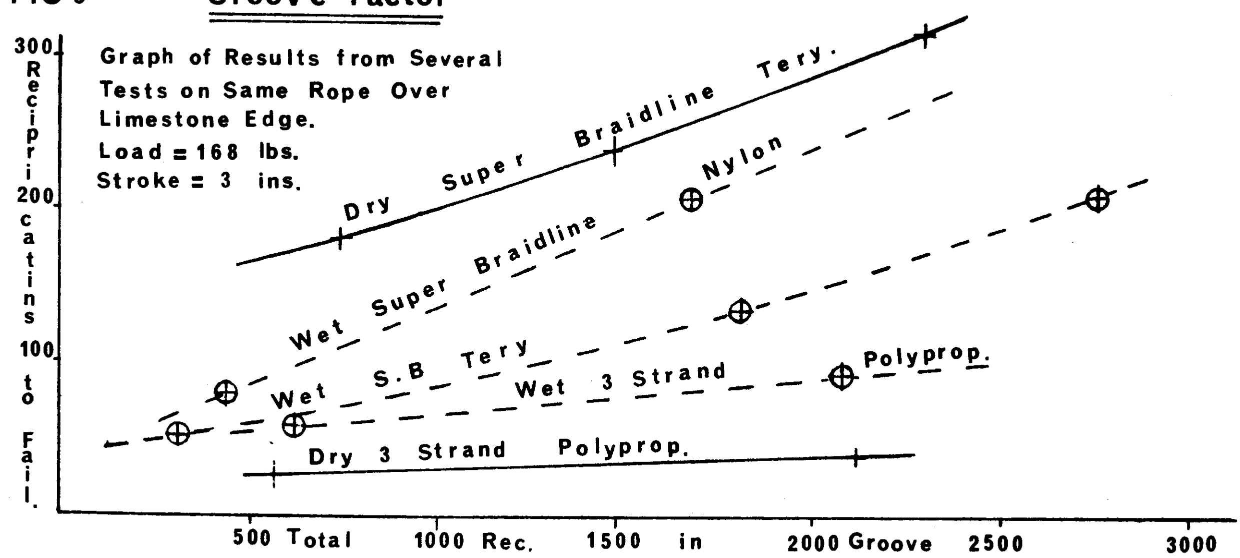
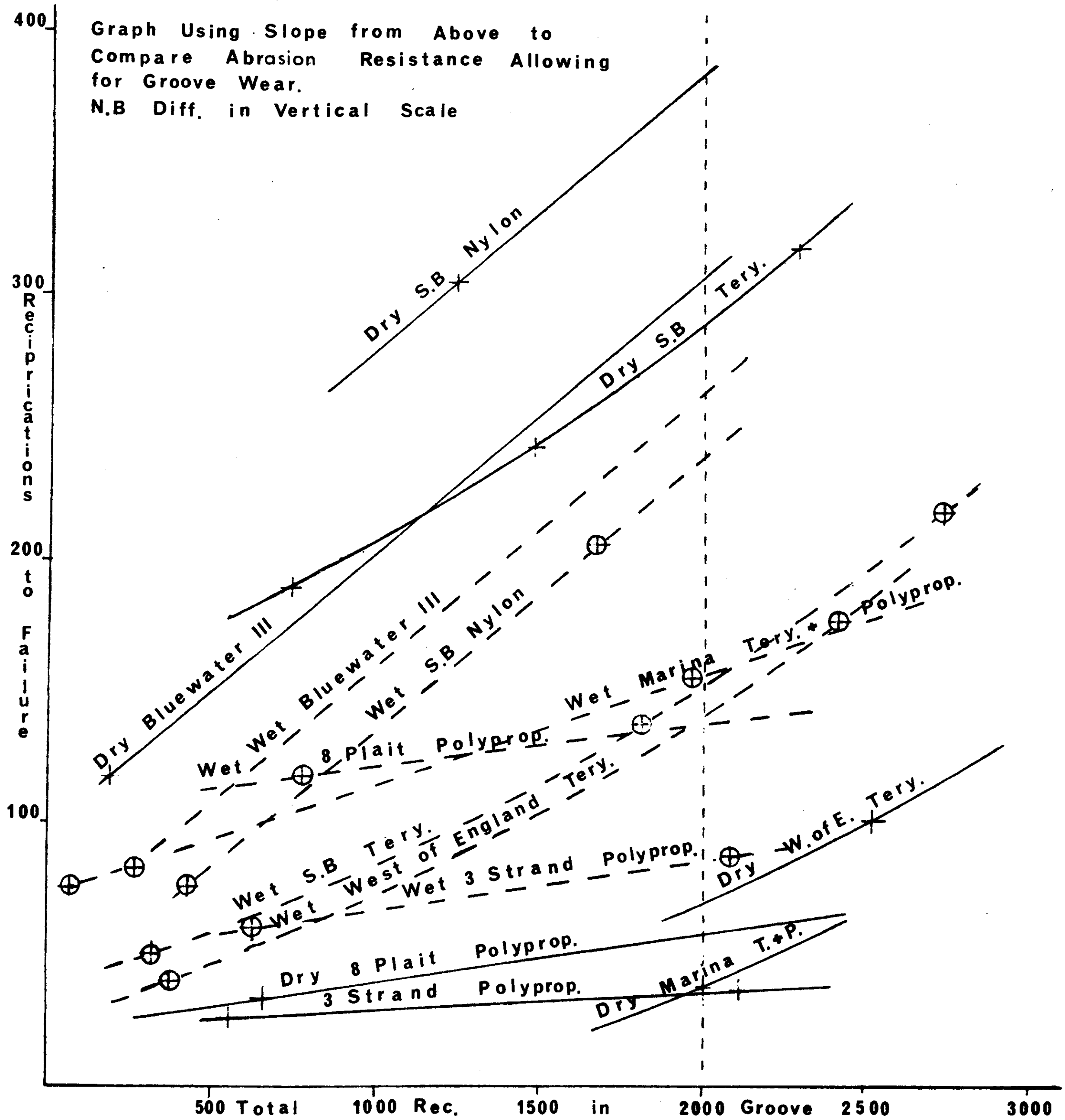


FIG 10



of limestone was clamped to a steel tressle which was in turn clamped to the lathe, and an anvil used to represent the author's weight (see Figs. 7 & 8). One end of the rope was attached to a large steel carabiner which was slipped over a 1½ inches round mild steel bar held in the lathe chuck. The bar could be moved from a central point on the chuck to a point 2 inches off centre. The rope went over the edge of the limestone block and the anvil was hung on the end. After the first test a piece of rubber matting was used to prevent further floor damage!

The initial series of tests were split into two types; one where the reciprocation distance was the same as that measured at Malham, the other with a constant reciprocation of 3 inches. Eleven ropes were abraded through on the first occasion and seven of these were new. It became obvious during the first set of tests that the groove produced in the limestone edge played a very important part. It had been hoped to use a new identical groove for each test but this proved impossible since small imperceptible differences in the groove made a great deal of difference to the number of reciprocations needed to abrade through. The results for the first tests using one groove are shown in Table 3. No correction has been attempted for the groove wear. Bluewater and Super Braidline nylon were the last two ropes tested so their figures are rather higher than would otherwise be expected. The reciprocation speed was 57 a minute, the slowest the lathe would go, which corresponds to a rather fast prussik. Notice the great difference in the figures for nylon and polypropylene ropes wet and dry, whereas the terylene rope is much less effected. The results suggest that dry Bluewater is over three times as abrasion resistant as when wet, whereas the plaited polypropylene figures suggest it to be over four times as abrasion resistant wet rather than dry. Melting is an important factor with polypropylene whereas fibre softening after absorbing water affected the nylon. It should be pointed out that the heat caused by the friction dries the ropes out very quickly. If the polypropylene did not have water poured on it continuously it started to melt after the water had come off as steam in four or five reciprocations; less heat seemed to be generated with the nylon although it did dry out. What this means in practice is that unless water was actually running down the rope abrasion resistance would be closer to the dry figure than the wet one for all types of rope.

An attempt was now made to correct for the groove wear. It was decided for this test to use a set stroke of 3 inches with a weight of 168 lbs. The idea was that on various occasions between testing the various ropes, previously tested ropes would be re-tested repeatedly wet and dry so that curves of these ropes' abrasion resistance against total receiprocations in the groove could be drawn (Fig. 9). The results for all the new ropes tested are shown in Fig. 10 with lines drawn parallel to the "groove lines". If a vertical line is now drawn through the graph at a point where the groove has had 2,000 reciprocations in it, the intersection of the curves should give a better comparison of abrasion resistance (see Table 4). The order is little changed but the gaps have been shortened; this is partly due to taking account of the groove wear and partly due to the constant stroke. Doing this exercise obviously has its limitations: many graphs have been drawn with rather a shortage of points, the time consuming nature of these tests being the main reason. Without falling into the trap of concluding too much from these abrasion tests, several interesting things are emerging. The affect of water is obvious, improving polypropylene and adversely affecting nylon. Bluewater is first or second in each case with the Bridon Super Braidline nylon behaving well. Polypropylene is generally low on the lists with Hawser laid polypropylene last in every case, melting played an important part in the figure of dry polypropylene ropes, the heat being generated in very few cycles.

Due to the shortcomings of the previous tests, it was decided to do a new series of tests using a different identical concrete edge for each test. At this time Ben Lyon very kindly donated some samples of rope he sells to enable the tests to cover most of the possible SRT ropes available in U.K. at the present time. Due to the poor results from the polypropylene ropes and the reservations mentioned earlier in connection with abseiling and melting point, it was decided to exclude these from the tests. The sample length of Bluewater had all been used by this time so unfortunately this could not be further tested.

The next problem was to find the right edge for the tests. Three edges were tried using Bridon Super Braidline terylene (see Fig. 11). Notice the tremendous difference both edge diameter and reciprocation length make, pointing to selecting belays carefully and keeping them as short as possible. Edge No. 2 was selected as giving a reasonable compromise between accuracy and time taken on the tests. Various strokes were used as measured at Malham. When dry the Bridon Super Braidline nylon was the most abrasion resistant, whereas when wet both nylons were the worst. Once again the terylene was least affected by water particularly the pre-stretched form which absorbed very little water. The very large difference between the 12mm Marlow terylene figures wet and dry was due to its large bulk acting as a heat insulator, so that when dry it primarily failed by melting; this was not the case when wet. It is possible the different type of rock played a part, soft fine-grained rock like the limestone used affecting certain types of fibre more than others. Solari, in his paper states, "Under some conditions when ropes rub on smooth surfaces or on fine abrasives, nylon has a greater resistance to wear than any other rope making material, natural or synthetic. But over coarse surfaces or with really coarse abrasives, nylon ropes wear much more rapidly than do manila ropes." This seems to be the case here, nylon performing very well on limestone with only very fine grained abrasive particles, whereas on coarse grained concrete it is not so good. This of course points to a source of error when using results from concrete and applying it to caving, highlighting the problems with trying to do meaningful abrasion tests.

Some old ropes were tested for abrasion resistance but a comparison with new ones was very difficult since most ropes obtained in the same construction old and new were polypropylene (Table 5). The degradation of rope materials, particularly nylon with time, must reduce their abrasion resistance to an unknown degree.

Table 4. Results of Second Series of Abrasion Tests using Concrete Edge.

Weight 168 lbs. Variable Stroke.

Order of Abrasion Resistance	Rope	Stroke	Time to Failure in minutes	Number of Reciprocations to Failure
	DRY			
1.	Super Braidline Nylon 10mm	3½"	6.00	342
2.	Marlow 16-plait Tery. 12mm	2"	3.16	180
3.	Super Braidline Tery. 10mm	2"	2.30	131
4.	Viking Log-Line 13mm	4.1/8"	2.21	126
5.	Marlow 16-plait Tery. 10mm	2½"	2.16	123
6.	Marlow Pre-stretch Tery. 10mm	2"	1.65	94
7.	Marina Braidline 10mm	3"	0.44	25
	WET			
1.	Marlow 16-plait Tery. 12mm	2"	7.85	449
2.	Marlow Pre-stretch Tery. 10mm	2"	1.67	95
3.	Super Braid Terylene 10mm	2"	1.51	86
4.	Marlow 16-plait Tery. 10mm	2½"	1.49	85
5.	Marina Braidline 10mm	3"	1.26	72
6.	Super Braidline Nylon 10mm	3½"	0.96	55
7.	Viking Log-Line 13mm	4.1/8"	0.96	55

Table 5. Old and New Tests.

POLYPROPYLENE (from first tests groove 1.)

Rope	Reciprocations to Failure Dry	Reciprocations to Failure Wet
Old Plaited 12mm	38	96
New Plaited 12mm	38	163

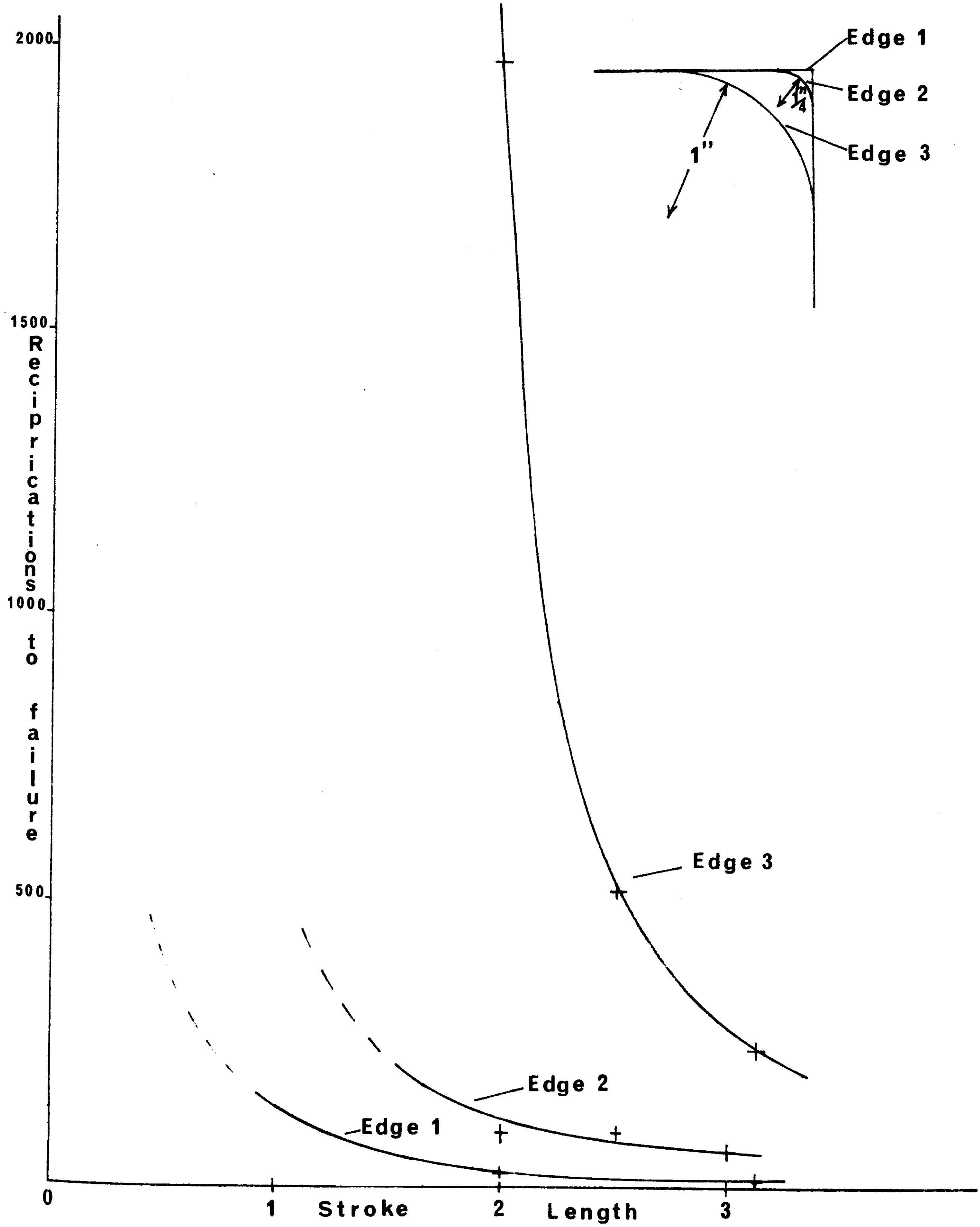
NYLON (from second series of tests as in Table 4)

Rope	Reciprocations to Failure Dry	Reciprocations to Failure Wet
Old Viking Log-Line 13mm	73	63
New Viking Log-Line 13mm	126	55

FIG 11

Graph showing the effects of edge radius & stroke length on abrasion resistance.

The rope used was Super Braidline terylene at 10mm. with a load of 168 lbs.



A comparison of rope constructions against abrasion resistance was not easy either since it depended on what criterion one used. All the tests were measured to complete severing of the rope. This was fair enough with Hawser laid and single plait ropes but once the sheath on Kernmantel ropes had failed it always slipped appreciably when held in the testing rig by ascending devices. In practice this would be the failing point of the rope since prussiking around the lump of sheath would be very difficult, and even if accomplished the Kernmantel core would be difficult to ascend. Double sheathed Kernmantel ropes like the Marlow non-prestretched terylene gave two chances to ascend before having to depend solely on the core, as the two sheaths did not slip very much one over the other when held by the ascenders. Double plaited ropes seemed to be the optimum since when the sheath abraded through there was minimum slip on the plaited core and this was gripped very well by the ascending devices used.

Ultimate Tensile Strength

As mentioned earlier, ultimate tensile strength tests on the club polypropylene were how it all started. All the ropes that were used in the abrasion tests were also tested in the tensile machine.

A few of the more interesting results from the first tests are summarized in Table 6. The results of the tests on the length of ropes with flaws in were particularly interesting: in general the ropes were only slightly weakened by a flaw. This is presumably because the flaws in the plaited construction occur where there is a join in one of the fibre bundles. The ends probably overlap, so for a short distance there are nine rather than eight plaits; the flaws always occurred in a series of eight along a 20 to 30 feet length of rope. Where these were bad flaws, however, prussiking might be affected.

Table 6. Ultimate Tensile Strength Tests on Polypropylene Rope.

Rope	U.T.S. as tested.	Manufacturers' figures
West of England ropes, 8-plait 1½" (12mm) rope used quite regularly for about one year.	1,630 lbs	3,000 lbs.
Rope as above but with a flaw.	1,370 lbs.	3,000 lbs.
Rope as above but new and unused	*(i) 2,460 lbs. (ii) 2,840 lbs.	(i) 3,000 lbs. (ii) 3,000 lbs.
New rope as above but at a bad flaw	(i) 2,300 lbs. (ii) 2,700 lbs.	(i) 3,000 lbs. (ii) 3,000 lbs.
West of England rope, 8-plait 1¼" (10mm) much used over approx 2 years.	900 lbs.	2,220 lbs.
As above but only about 1 year of use.	1,530 lbs.	2,220 lbs.

* Two different new ropes.

Several nylon ropes were tested at this stage but for many of them the owners did not know the name of the manufacturer and so new figures could not be obtained. There was one type of plaited nylon rope where maker and history was known.

Rope	U.T.S. as tested.	Manufacturers' figures
Viking Log Line 12.5mm, 8-plait nylon with straight core, rope much used over two years	3,000 lbs.	4,250 lbs.
As above but very old. Detailed history unknown – (Donated by Bob Churcher)	1,680 lbs.	4,250 lbs.
Similar rope obtained from entrance to Magic Roundabout series in Lancaster Hole that had been removed because it was considered dangerous.	2,700 lbs.	4,250 lbs.
Brand new rope as above.	3,700 lbs.	4,250 lbs.
Very old Hawser laid 12mm nylon, surface abraded and at least 5 years old.	1,930 lbs.	unknown

No old terylene ropes were available. A new polypropylene rope was tested as above, then re-tested six months later without being used and kept cool and in the dark. There was no appreciable difference between the ultimate tensile strength figure of 2,700 lbs. in March 1974 and 2,650 lbs. in September. Knots were also tested at this time and the figures were very similar to those quoted by Hamish MacInnes in his book "International Mountain Rescue Handbook".

Knots for joining two ropes

Ropes spliced	80–90% of rope strength
Fisherman's knot	60–65%
Sheet bend	60%
Reef knot	55–60%

Knots for attaching rope to carabiner, etc.

Eye slice	85–95% of rope strength
Tarbuck knot	80–90%
Bowline	70–75%
Figure of 8	70%

(Figures from the handbook)

Some other knots were tested: two ropes were joined by a figure-of-eight knot which gave a poor 50% and a simple overhand knot also gave about 50%.

Some notes are now appropriate on the testing procedure. A Denison Machine was used capable of giving a maximum load of 50 tons in tension or compression, the maximum separation of the jaws was 24 inches. For these tests the ropes were held in flat knurled jaws, thick masking tape being wound around each end of the specimen length to protect the rope fibres from being cut by the jaws. In practice, if the rope parted somewhere near the centre the test was believed to give a reading near to the actual ultimate tensile strength. If it failed at one end steps were taken to try to reduce end effects. With sheathed ropes an overhand knot was tied in each end of the specimen length above and below the jaws to reduce sheath slippage (Fig. 12). On occasions however the core failed against the knot at the outside of the jaws, so the holding method was modified (Fig. 17). Two short pieces of 2 inches diameter mild steel bar were clamped in the jaws and the rope was then wound aroudn them, the ends being tied off to another bar across the jaws. It was believed that this must reduce end effects to a minimum and the results obtained should be within 10%, although the ropes did not always fail in the centre.

Ultimate tensile strength tests were now done on all the ropes used in the abrasion tests (Table 7). Wet and dry tests were done on several ropes with very little difference between the results. Nylon as expected was the most affected with about 10% reduction in ultimate tensile strength when wet. The ropes failed by various means, the reasonably new plaited ropes tended to part one fibre bundle at a time giving a very progressive effect. Old plaited ropes, however, where the stress in each fibre bundle was more likely to be the same, went instantly all fibres at once. The core of some of the Kernmantel rope tended to go first, the sheath following quickly. With the double plait ropes the sheath and core tended to go at the same instant, with the exception of the Marina Braidline mixture where the polypropylene core failed first. Double plait construction seems to be a good one since both components of the rope have similar elastic properties (when both made of the same material) and hence act together to give a high ultimate tensile strength.

Some ascending devices were now tested and the tests will be only briefly mentioned here. 12mm plaited polypropylene slipped through a clog ascender at 844 lbs. (Fig. 15). When a knot was tied in the rope the rope broke at 1744 lbs. When the same thing was done with a very short length of Bluewater III the clog turned inside out at the same moment as the rope failed at 3,938 lbs., a very commendable figure. The cam on a Petzl ascender distorted at 800 lbs. under the same test conditions using Super Braidline Terylene. Tests on Jumars and Gibs would be very interesting, but a donor has yet to be found. Failure at the knot always occurred on rope to carabiner tests rather than at the point where the rope went round the carabiner.

Table 7. Ultimate Tensile Strength Tests on New Ropes

Rope	Manufacturer	U.T.S. measured (lbs.)	U.T.S. quoted by manufacturers (lbs.)
POLYPROPYLENE			
Hawser 12mm	Unknown	2779	–
Plaited 12mm	West of England Ropes	2925	3000
TERYLENE			
Braidline Super Polyester 10mm	Marina Yacht Ropes	4219	3960
Matt Plaited 10mm	West of England Ropes	1689	3000
16-plait matt finish 10mm	Marlow Ropes	3234	3500 (quoted in Jan.70) 4400 – Jan.73
16-plait matt finish 12mm	Marlow Ropes	4940	5500 (quoted in Jan.70) 6600 – Jan.73
8-plait pre-stretched 10mm	Marlow Ropes	3040	3500

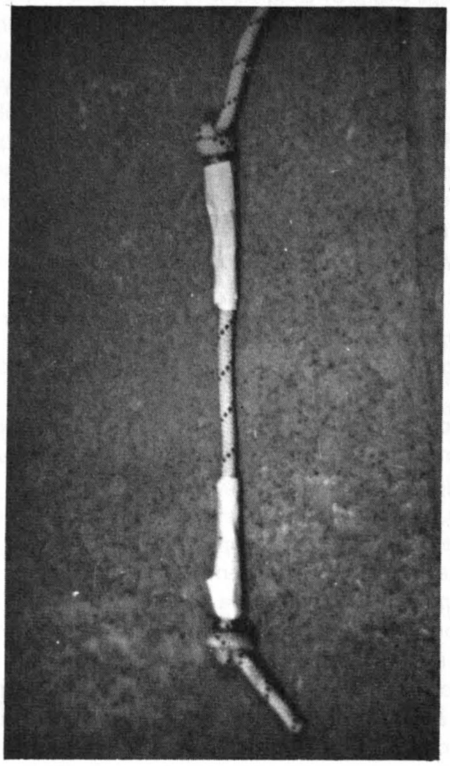


FIG 12

Length of Blue Water III about to be U.T.S. tested.

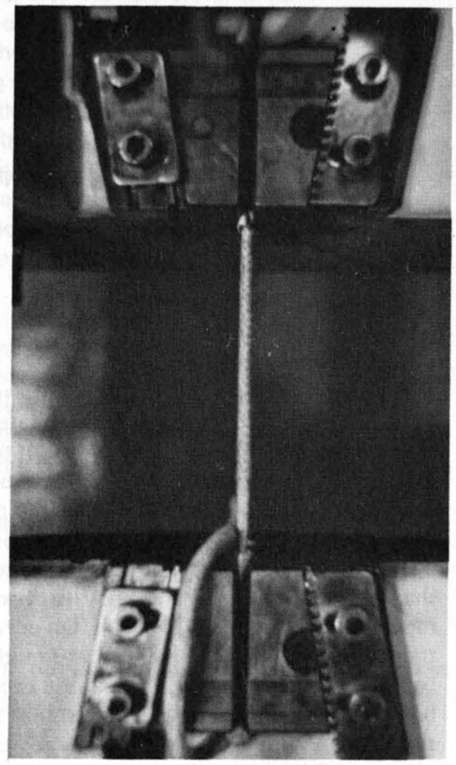


FIG 13

Plaited Terylene rope under test.

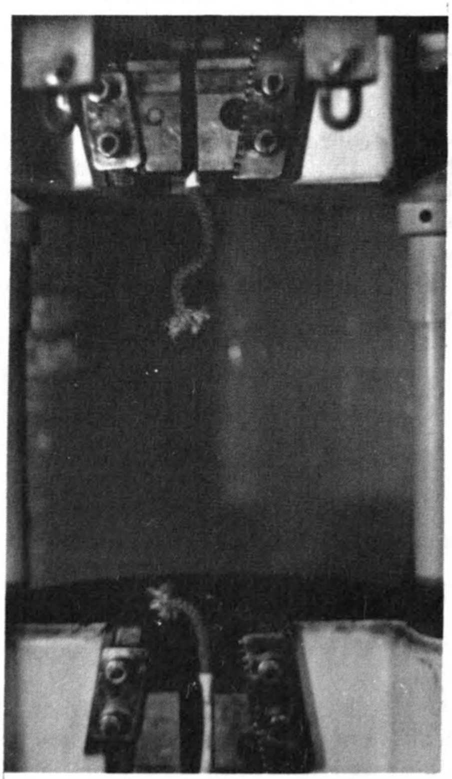


FIG 14

Plaited Terylene rope after failure.

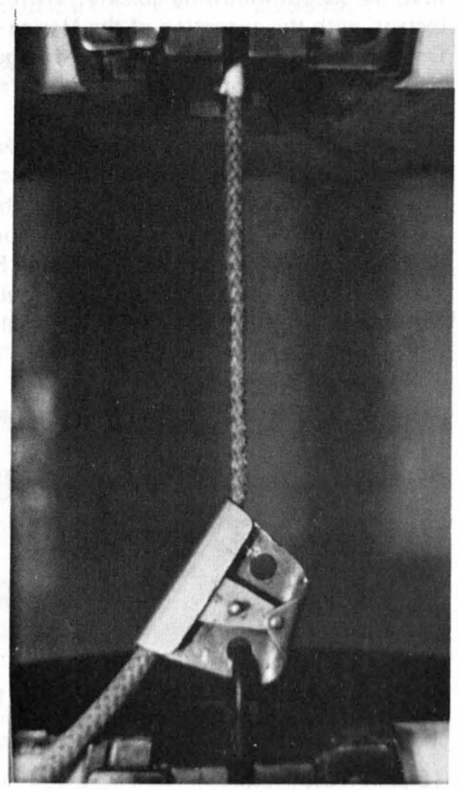


FIG 15

Plaited Polypropylene rope slipping through clog ascender.

Table 7 (continued)

NYLON			
Blue Water III 12mm	Blue Water Ltd.	3938	7000
Viking Log-Line 13mm	British Ropes	3700	4250
Braidline Super Nylon 10mm	British Ropes	3386	6000
POLYPROPYLENE/TERYLENE MIXTURE			
Marina Braidline 10mm	Marina Yacht Ropes	2250	2500

N.B. The highest figures obtained from a series of tests have been used.

Price

Rope price is obviously a very important criterion and forms a compromise in the same way as rope weight. Bluewater was probably the best rope tested but its price of around £45 for 300 feet is virtually prohibitive. For the same money 600 feet of other good rope can be bought.

Rope prices are in a state of flux at the present time. The closing of I.C.I.'s polypropylene plant has raised the price of this to near nylon and terylene. The Flixborough disaster is resulting in a shortage of nylon, making people use terylene as a substitute which in turn is making this more expensive. It is always preferable to deal direct with the manufacturers since you can then be sure that the figures quoted apply to the correct rope and they will also in general be cheaper. If the manufacturers are not forthcoming, reputable dealers will give upto 25% on the figures quoted here for orders of 300 feet or more.

Theoretical Considerations of Rope Strengths

Several people over the years have had methods of calculating the required strength and this is just another of them aimed specifically at abseiling and prussiking. It contains several gross assumptions and, if used at all, should only be a guide.

The most likely way of applying a breaking load to a rope is to load it dynamically. In SRT work the most likely way of doing this is as shown in Fig. 16. One man ascends a pitch with a ledge part way up, but unfortunately when he starts up the final section the rope gets snagged beneath him. The next man up gets to the ledge just as the rope is released and he drops x feet;

then by Pythagorus $x = Y + Z - \sqrt{y^2 + z^2}$

For x to be a maximum $y = Z$ (i.e. the width of the ledge is equal to the distance from the belay above). This gives $x = 0.585Z$. Climbing magazines (see Climber and Rambler October 1974) use a fall factor to categorize these falls.

$$\text{Fall factor} = \frac{\text{length of fall}}{\text{length of rope to belay}}$$

A fall factor of 2 is called an extreme fall and any below 1 are called soft. The example here gives a fall factor of 0.293 a low figure; it is of course applied to a stretchy nylon climbing rope.

Now from John Letheren in Descent 25, assuming the rope would fail at 50% elongation, which from the U.T.S. tests seemed a reasonable figure for nylon.

$$\text{Peak tension in the rope on fall} = M + \sqrt{M^2 + \frac{4MHW}{L}}$$

where M = Mass of caver
H = Distance he falls
L = Length of rope to belay
W = U.T.S. for rope

Now with the fall of x above,

$$\text{Peak tension} = M + \sqrt{M^2 + 4MW\ \frac{0.586Z}{2Z}}\ ^*$$

* Fall factor and as above Z cancels out, so it is independent of the scale.

$$\text{So } (PT - M)^2 = M^2 + 1.172MW$$

$$PT^2 + M^2 - 2PTM = M^2 + 1.172MW$$

Cancelling M^2 we can let the weight of the caver equal 150 lbs. and if we let $W = PT$ (i.e. the rope just sustains the fall.)

$$W^2 - 300W = 1.172 \times 150W$$
$$W = 476 \text{ lbs.}$$

So a nylon rope with an effective strength of 476 lbs should hold any fall likely to be encountered in SRT. Now to get to the manufacturers' quoted figures from the effective strength above a x2 factor is needed to take account of the knot, then another times 2 factor to take account of rope degradation etc., so a figure

FIG 16 **Theoretical Exercise on Rope Strength.**

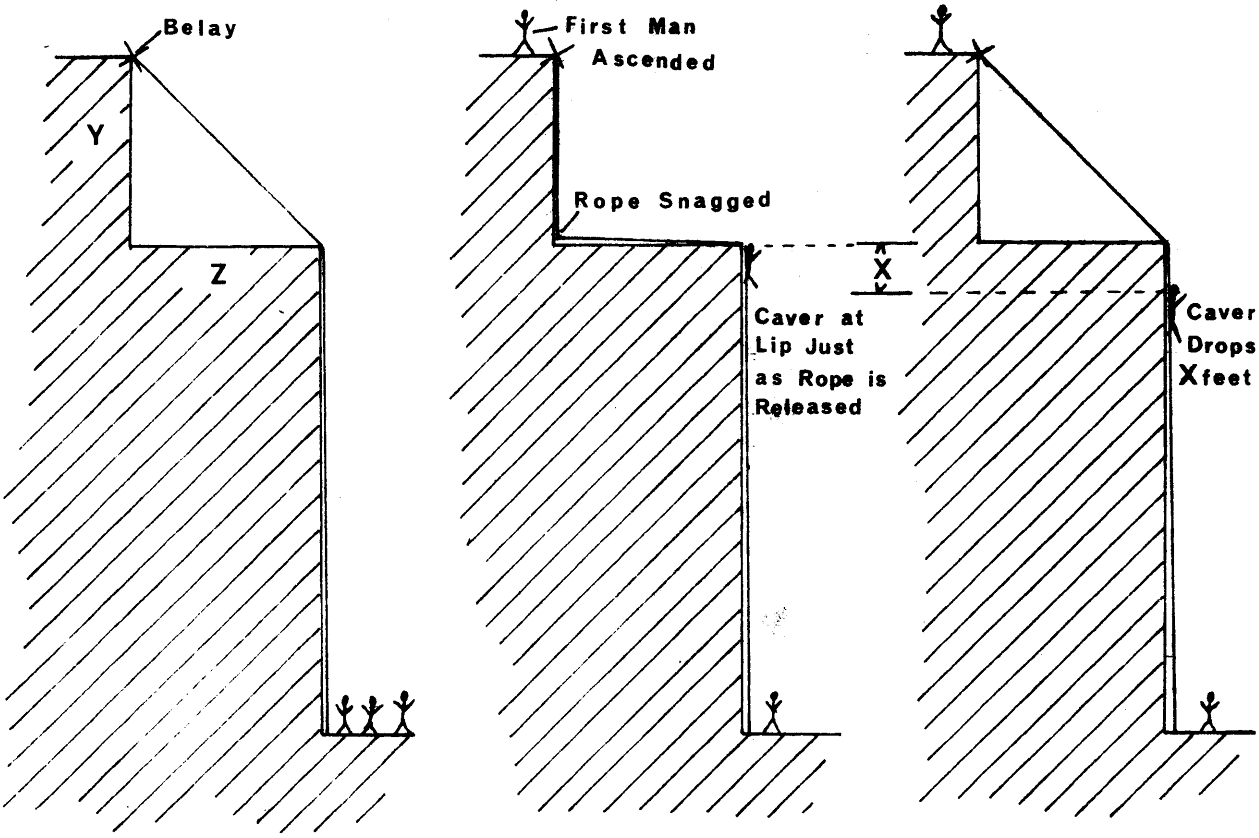


FIG 17 **Method of Reducing End Effects in U.T.S Tests.**

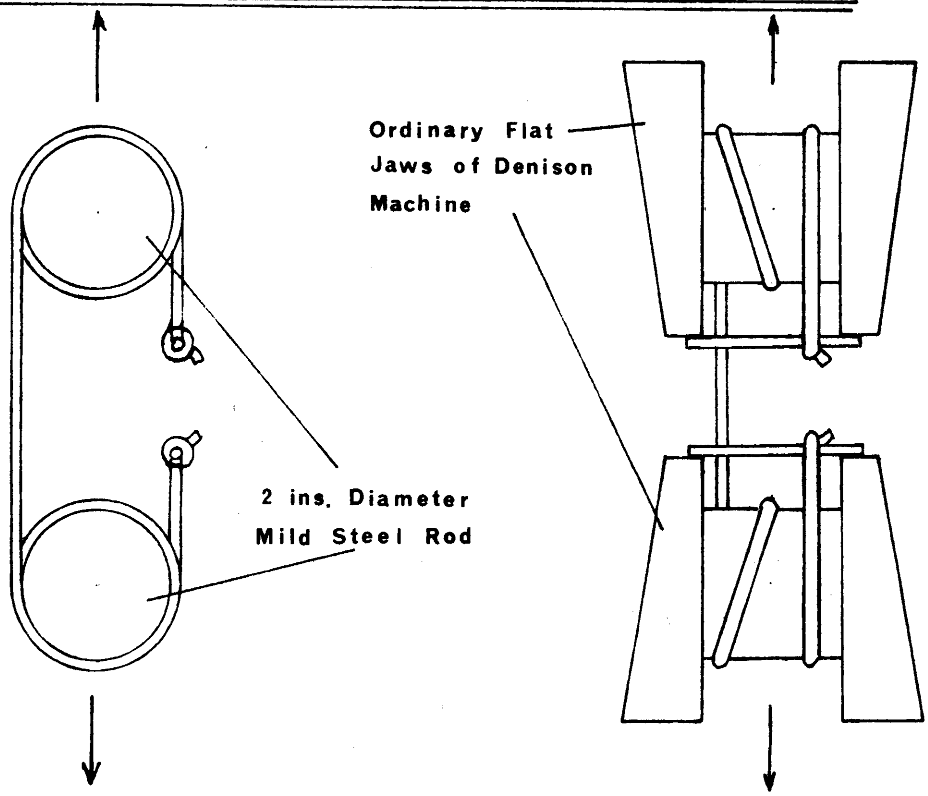
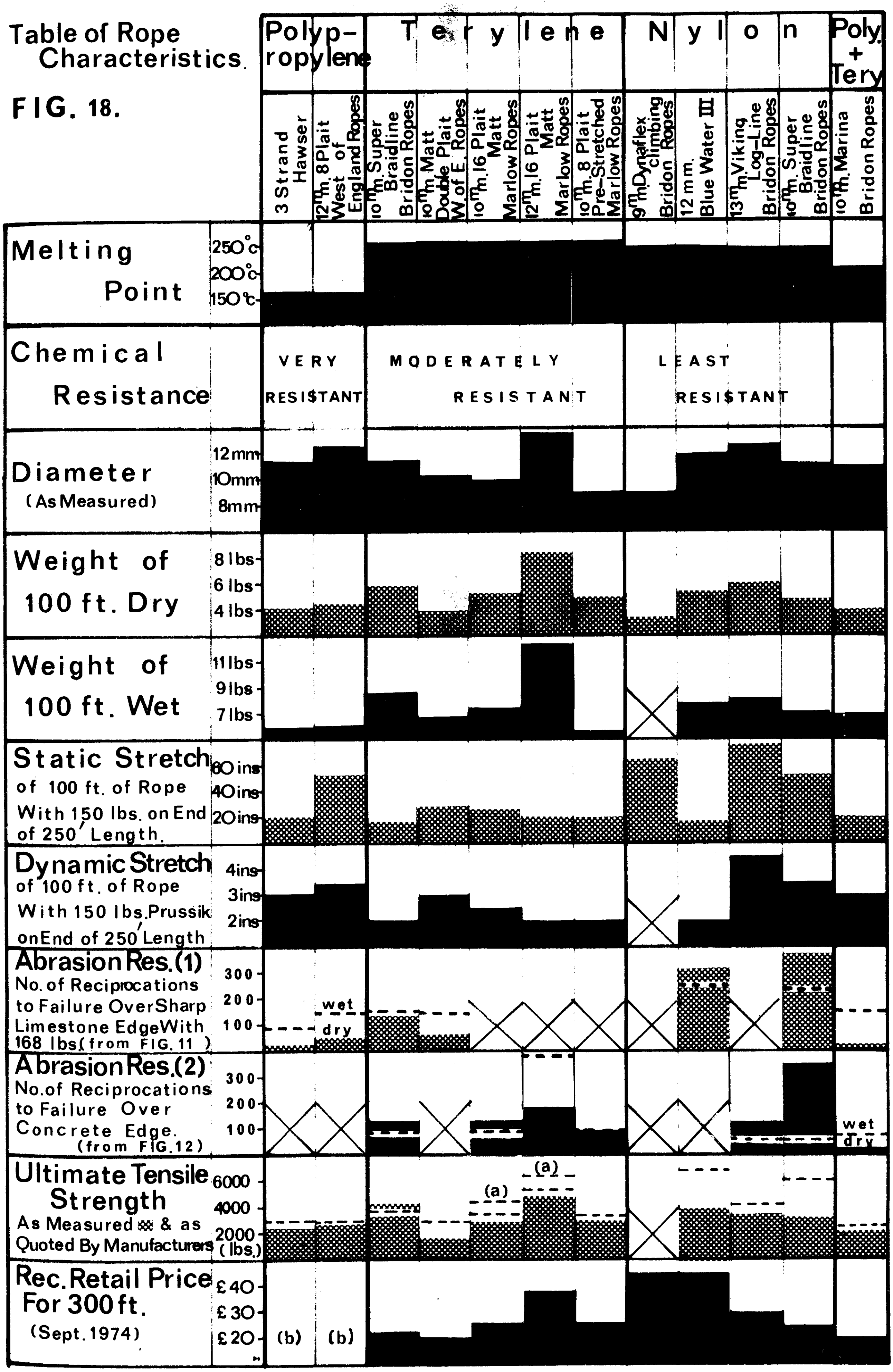


Table of Rope Characteristics.

FIG. 18.



(a) U.T.S Quoted By Marlow Before Jan. 1974 Much Lower Than Present Figure.

(b) These Particular Ropes Are No Longer Available. Equivalent Ropes By Bridon Or Marlow Are Approx. £20 For 300 Ft.

of about 2,000 lbs is reached. In the author's opinion this should be regarded as an absolute minimum and probably needs increasing by 50%.

Conclusion

The individual sections have been concluded as far as possible through the paper to minimise comments here, but there are a few things to emphasize.

Polypropylene ropes are undesirable for SRT due to their low melting point and all ropes particularly nylon need careful protection from household chemicals, heat, sunlight, etc. Hawser laid ropes are out due to spin. Beware of retailers and, if possible, look at and measure your ropes before buying. Weight and price must be borne in mind and a compromise decision made. Static stretch is usually a nuisance as is dynamic stretch on big prussiks. A word of warning, however, if a fall is to be sustained by a rope with a low dynamic stretch, the forces will get very high and could break the rope and the caver in two. Figures for the maximum a body can stand are quoted in the Climber and Rambler, October 1974. With this type of rope it is obviously imperative to avoid falls by making sure the ropes are well belayed and do not get snagged, re-belaying at ledges etc.

The abrasion tests are only supposed to be a rough guide. A good testing system was discovered but due to lack of time really exnaustive tests could not be undertaken. Possibly a way around the groove factor problem would be to test a block of homogeneous limestone with an edge of approximately ¼ inch radius cut all along one side. A new part of the edge would then be used for each test. The abrasion tests do, however, point out the effects of water on the ropes and the great importance of a short belay, non-stretchy rope and careful edge selection. The abrasion tests were aimed specifically at fast, potentially lethal abrasion, but they are obviously a pointer to general abrasion from ropes being dragged round caves, etc. Ropes must be protected as much as possible from abrasion of this type by the use of tackle bags, etc. that can also be used as edge protection at the pitch top. Nylon ropes should also be kept dry if at all possible.

In all but one case the U.T.S. figures were below those quoted by the manufacturers and degradation since the rope was made is the probable cause. Nylon is the most affected by this ageing effect and the nylon figures in general were where the biggest discrepancy arose.

Personal preference has been towards the double plait and double sheathed terylene at 10mm diameter, e.g. Bridon Super Braidline and Marlow 16 plait, the latter unfortunately only available as matt finish. These ropes are nice to handle, not very stretchy, very strong, reasonably abrasion resistant and comparatively cheap. They are, however, quite heavy. The matt finish ropes means the surface fibres are composed of short lengths rather than continuous filaments which are probably preferable.

Acknowledgements

The author wishes to extend his thanks to Dave Brook, Alan Goulbourne, Bob Greenwood and members of the two ULSA 1974 expeditions to Malham Cove. Thanks also go to Ben Lyon and Pete Lord, who donated ropes, as well as to Leeds University Mining Department for use of their Denison Machine.

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Received 5th November, 1974

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Editorial Note.

Since the above went to press a fatal accident has occurred in Gaping Gill. The victim apparently abseiled down the main shaft on a polypropylene rope and stopped for a rest on Birkbeck's Ledge. During this the heat in the descender melted the rope inside – unnoticed ....

Trans. British Cave Research Association. Vol. 1. No. 4. pp.199-214. December, 1974.

THE CHARACTERISTICS AND USE OF LEAD-ACID CAP LAMPS.

by M.F. Cowlishaw

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 1960, 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:

$$PbO_2 + Pb + 2H_2SO_4 \rightarrow PbSO_4 + PbSO_4 + 2H_2O$$

or more fully:

$$\left.\begin{array}{l} PbO_2 + 2H' \rightarrow PbO + H_2O + 2\oplus \\ \text{and} \quad PbO + H_2SO_4 \rightarrow PbSO_4 + H_2O \end{array}\right\} \text{Positive Plate}$$

$$Pb + SO_4'' \rightarrow PbSO_4 + 2\ominus \qquad \text{Negative Plates}$$

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

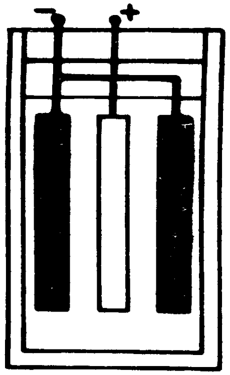
During this process the internal resistance of a battery rises from about 0.1 to 0.15 ohm, the actual value depending on its condition and age – in general a battery which is old or in bad condition will have a higher internal resistance.

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.

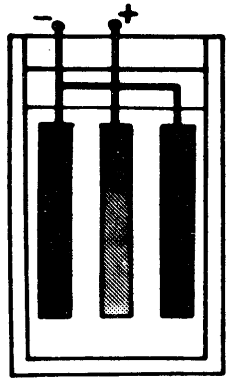
It will be seen from the discharge curve that the battery voltage remains close to 4 volts for most of the time. This is an important point as it means that bulbs can be used close to their optimum operating point for most of the period of discharge, which makes for high lighting efficiency.

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.

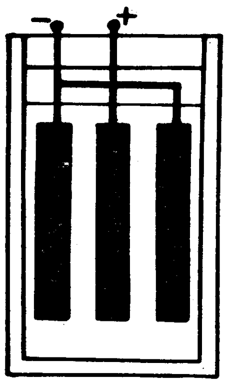
Occasionally during an unexpectedly long stay underground it might be necessary to exhaust a battery. A fact that may be unknown to some is that if such a battery is switched off and left to 'recuperate' for an hour, some chemical recombination occurs, and the lamp will then be found to give as much 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).



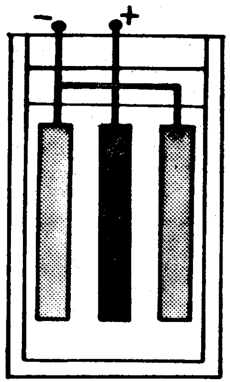
a) Fully charged cell.
+ve plate PbO_2
-ve plates Pb
Electrolyte at strongest.



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.

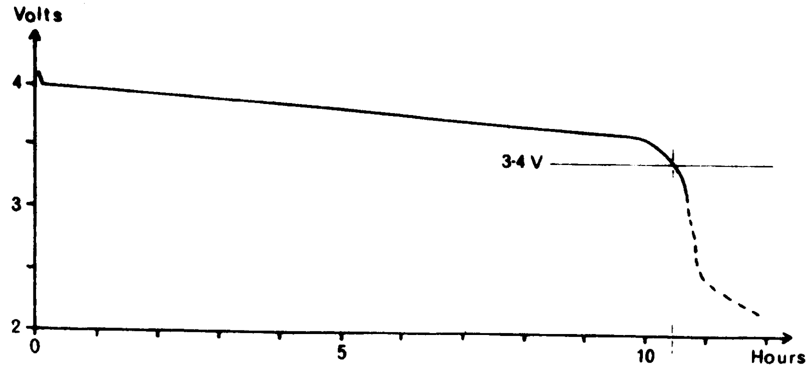


Figure 3. A typical discharge curve.

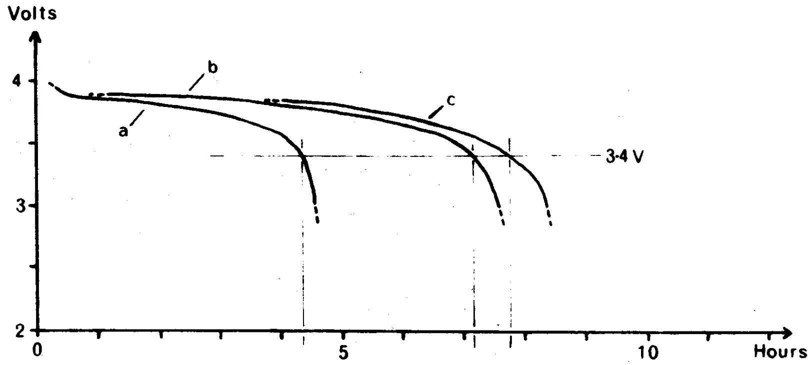


Figure 4. Discharge curves of a sulphated battery.
a) initial discharge curve.
b) after a reconditioning charge.
c) after a second reconditioning charge.

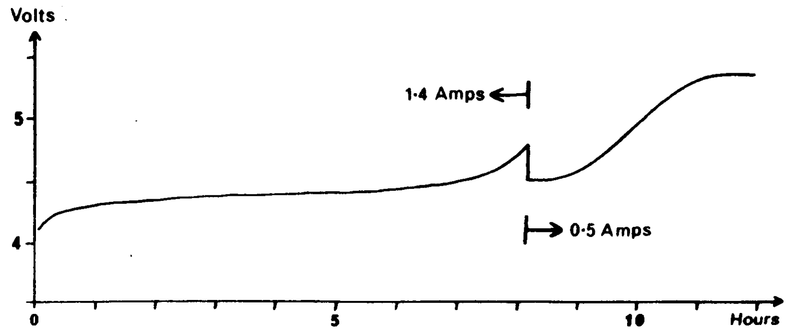


Figure 5. Voltage curve for constant current charging.

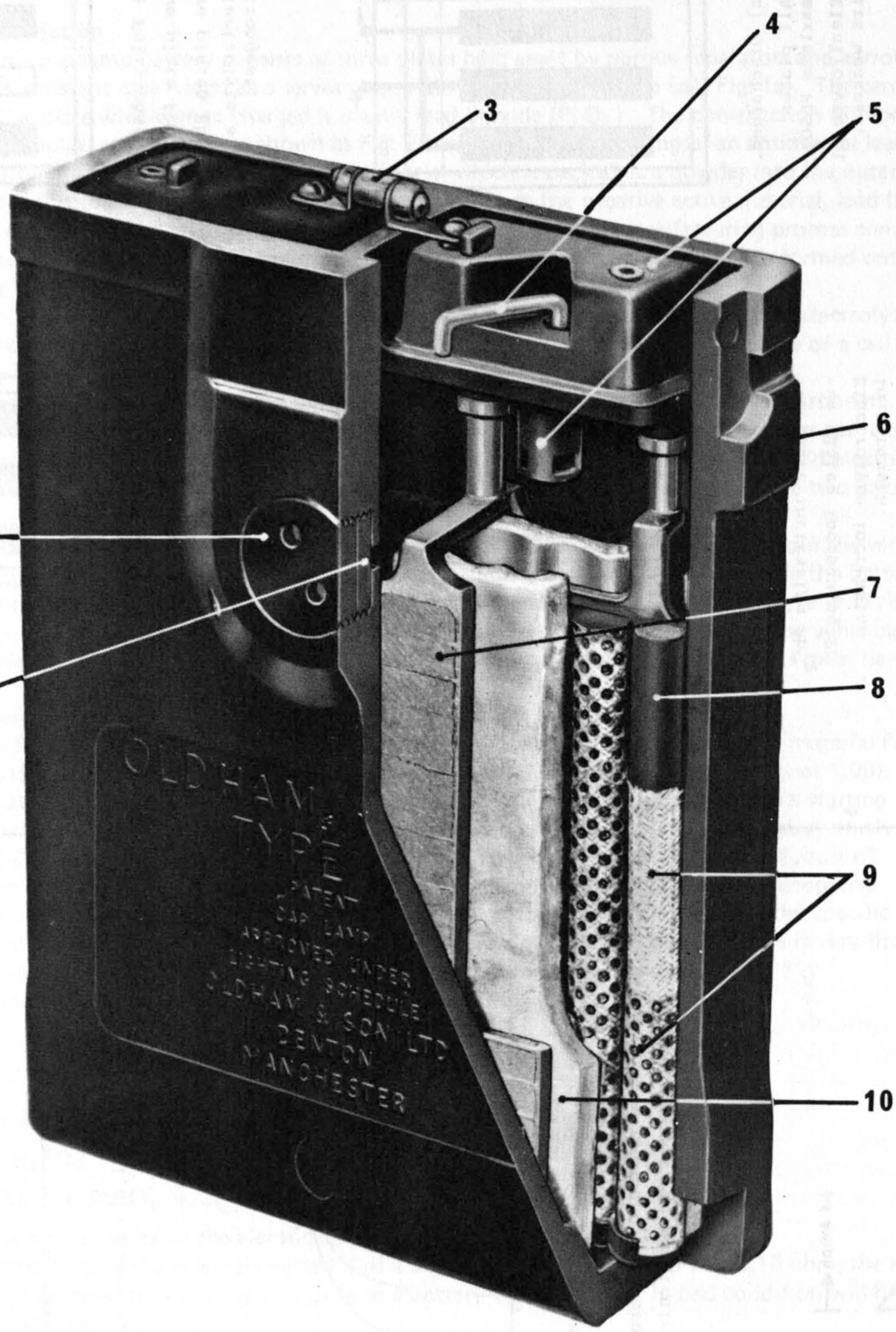


Figure 2. Sectional view of the Oldham type 'R' battery.

1) Rubber seal.
2) Removable plug for topping up.
3) Fuse.
4) Gas vent link.
5) Rubber lid with non-spill device.
6) Toughened hard rubber contai
7) Negative pasted plate.
8) Positive active material.
9) Porous sleeves.
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 electrolute becomes progressively stronger, the positive plate is converted to PbO_2, and the negative plates return to being spongy lead (Pb).

The simple chemical formula for this is:

$$PbSO_4 + PbSO_4 \rightarrow 2H_2O + PbO_2 + Pb + H_2SO_4$$

or more fully:

$$PbSO_4 + 2\ominus \rightarrow Pb + SO_4'' \qquad \text{Negative Plates}$$

$$\left.\begin{array}{ll} & PbSO_4 + SO_4'' + 2\oplus \rightarrow Pb(SO_4)_2 \\ \text{and} & Pb(SO_4)_2 + 2H_2O \rightarrow PbO_2 + 2H_2SO_4 \end{array}\right\} \text{Positive Plate}$$

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:

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

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:

$$I = 15 - 3E - 3I.r \qquad (3.4.2)$$

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

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.

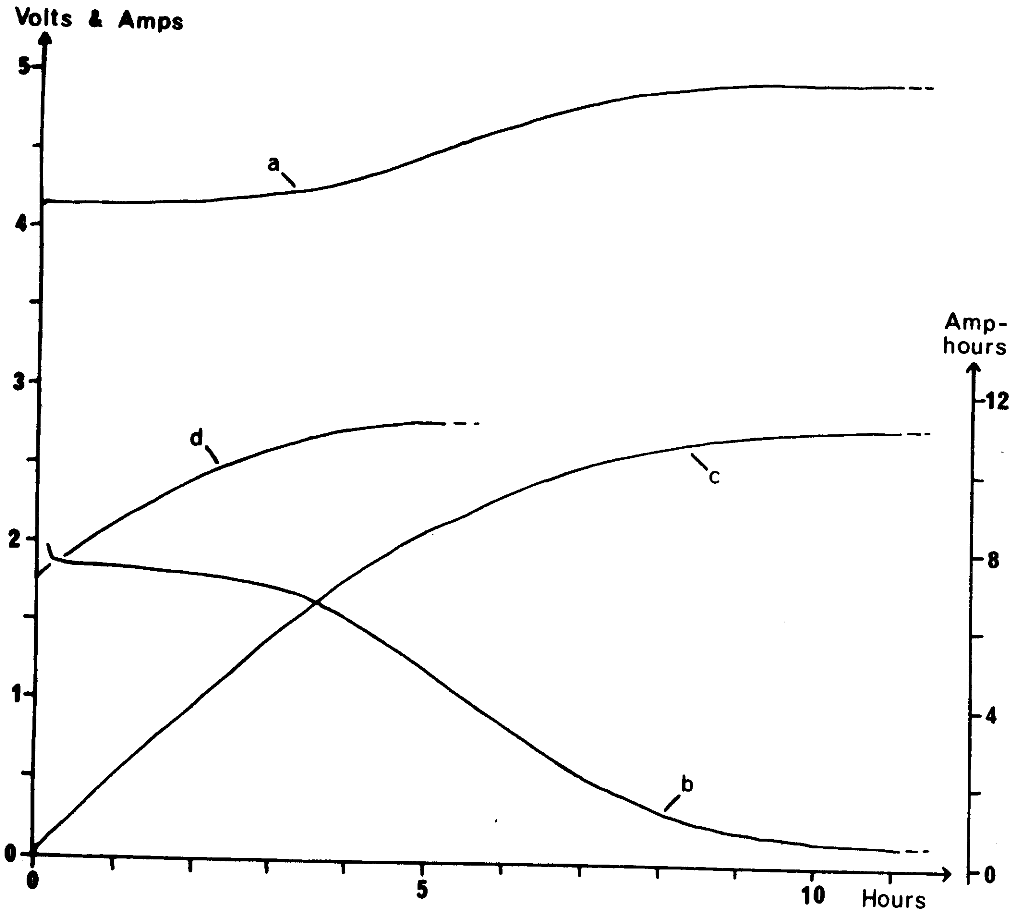


Figure 6. Modified constant potential charging.

a) Voltage curve. (E).

b) Current curve.

c) Amp-hour curve.

d) Amp-hour curve for a partially discharged battery.

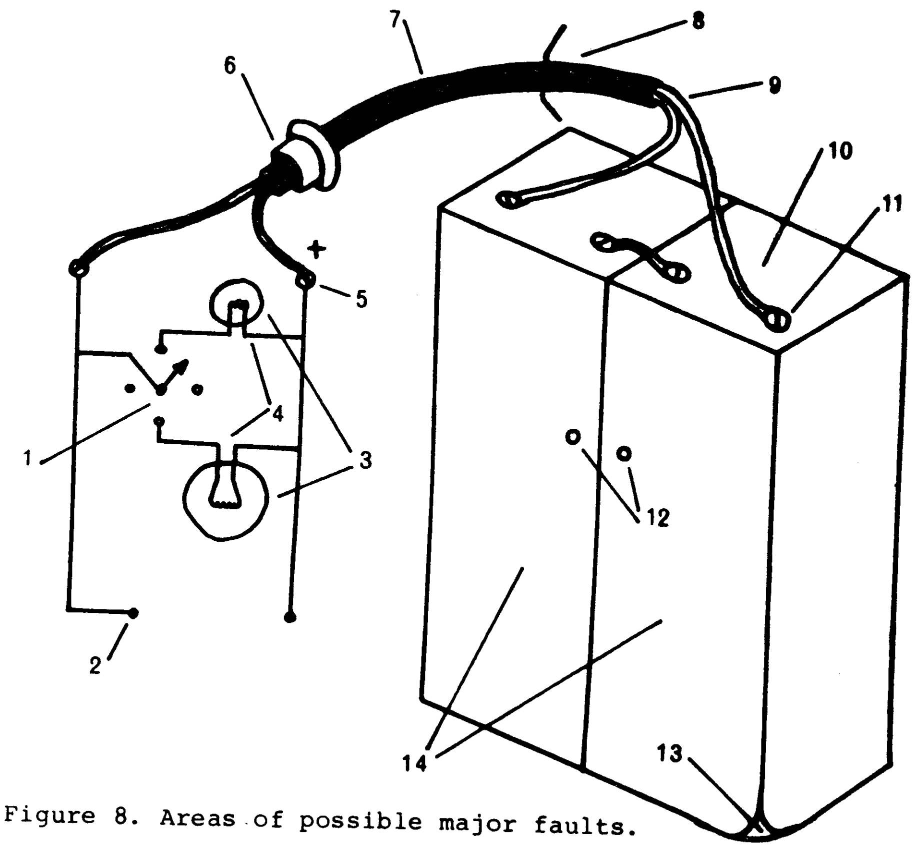


Figure 8. Areas of possible major faults.

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.

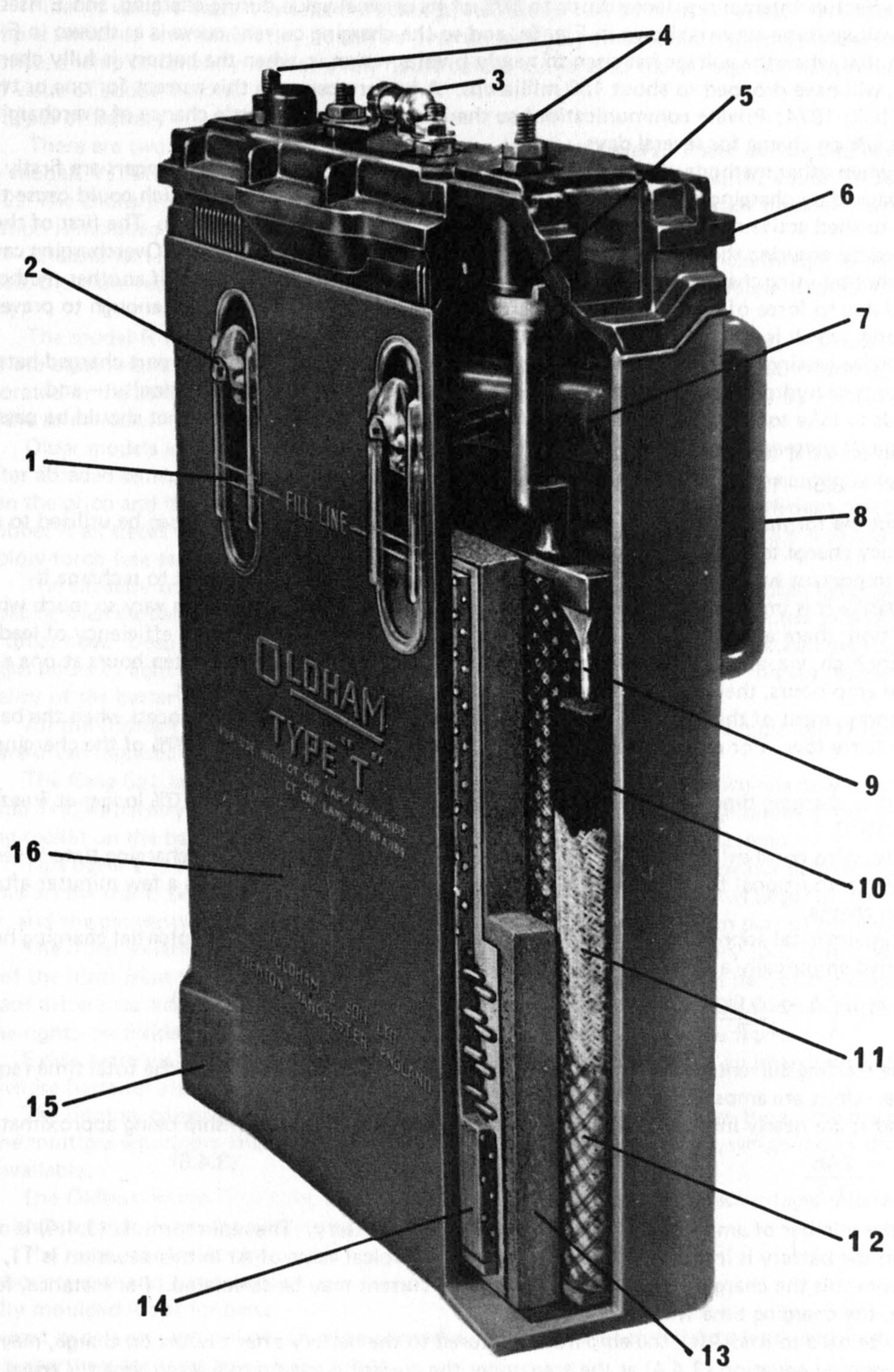


Figure 7. Sectional view of the Oldham type 'T' battery.

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

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

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:

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

where Is 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 Is are nearly inversely proportional, as stated above, the relationship being approximately:

$$T.Is = \frac{2Ah}{1.1} \qquad (3.4.5)$$

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 Ar in this situation is 11, so T.Is = 20. From this the charging time for a given starting current may be calculated. For instance, for Is = 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:

$$A(t) = {}_o\int^t I(t).dt = Is\left({}_o\int^t 1.dt - \frac{0.9}{T}\,{}_o\int^t t.dt + 0.2\,{}_o\int^t \sin\frac{2\pi t}{T}\right) \qquad (3.4.6)$$

$$= Is\left(t - \frac{0.9t^2}{2T} - 0.2\left(\cos\frac{2\pi t}{T} - 1\right)\right)$$

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:

$$A(t) = t.Is\left(1 - \frac{t.Is}{4Ah}\right) \qquad (3.4.8)$$

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. Is 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 Ogof 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 polychloropene 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 cavers 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 moficiations, 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.

Acknowledgements

The author would like to thank:

The Department of Electronic and Electrical Engineering at the University of Birmingham, for use of laboratory facilities;

Oldham and Son Ltd., for the photographs accompanying this paper, and for leaflets, offprints, etc.; and especially Dr. A.G. Neill, Mining Division Manager of that firm, for answering a long list of technical questions;

Ceag Ltd. and Chloride Industrial Batteries Ltd., for much useful information;

H. Nailor, A. Morley and J. Neill, for critical reading of the manuscript.

Final Manuscript received 17th August, 1974

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SOME PRELIMINARY OBSERVATIONS RELATING TO THE USE OF EARTH RESISTIVITY MEASUREMENTS FOR CAVE DETECTION.

by D.P. Creedy and J. Freeman

Summary

Magnetic, seismic, gravity and electrical methods have been used by various workers to detect underground cavities. Electrical resistivity appears to be the most useful property for exploiting in the detection of cavities in limestone. The analytical treatment of the Wenner depth probe, after Palmer, seems to be incompatible with natural situations. In geologically simple areas the graphically interpreted single electrode technique, after Bristow, shows the most promise, offering ease of field operation and rapidly available results.

Introduction

The aim of this review is to indicate the difficulties associated with the finding of caverns by geophysical methods. The problems will no doubt allay the fears of traditional cave searchers of being replaced by unethical methods.

The methods concentrated on herein are those available to any caving club with limited finance and expertise with access to the necessary equipment or the know-how to make it. We hope to stimulate a feedback of practical and theoretical ideas on the problems of remote cavity detection.

Geophysical detection methods depend on the variation in the physical properties of the lithologies below the test site. The properties employed are seismic wave propagation, specific gravity, magnetic susceptibility and electrical resistivity.

Seismic, Gravity and Magnetic Methods

Seismic techniques depend on the reflection or refraction of the shock waves from an explosion, usually detonated in a shallow borehole. The waves are picked up on an array of geophones linked to a recording drum and computer analysis is normally needed to interpret the results. Cook (1965) has detected underground cavities in salt horizons having dimensions of tens to hundreds of metres using seismic reflections from the top of the cavity and the tendency of the cavity to cut out reflections from deeper horizons (seismic shadowing effect).

A variety of extremely sophisticated seismic methods have been reviewed by Wigley (1974) but it is unlikely they will ever see widespread application due to the phenomenal cost of the equipment. Even with the assistance of computers the skills required to interpret seismic maps are not easily attained.

Gravity techniques depend on detecting slight variations in the attractive force, which may be caused either by variations in the shape of the ground, such as mountains, or by differences in the rock layers below ground. The readings from the gravimeter are converted to Bouguer anomalies by subtracting the effects of local topography; positive anomalies indicate dense rock below ground, negative anomalies may indicate either lightweight rock, such as salt, or hidden cavities.

Murphy (1962) obtained intense negative Bouguer gravity anomalies of very limited extent in Central Ireland above Carboniferous Limestone. The analysis indicated a "body" of density 2.2 to 2.4 $g.cm^{-3}$ .but no rock with a density of less than 2.5 $g.cm^{-3}$ is known to exist in the vicinity, thus a solution cavity filled with water or poorly compacted rock was proposed.

A gravity anomaly is not necessarily produced by a simple structure but may be due to the sum effects of unrelated structures at different depths. "Filtering" techniques may be used to eliminate underlying effects but even then a model has to be assumed. The dimensions of this postulated model are then calculated from the Bouguer anomaly. Due to the uncertainty of the interpretation an independent method, for example a resistivity technique, would be required to confirm the presence of a cavity at a given depth.

Magnetic methods depend on measuring differences in the magnetic field from the theoretical norm which may be due to differences in the nature of underlying rock. Hidden bodies of iron ore or of iron-rich rock may be detected easily, but since limestone has a low magnetic susceptibility, the method is not usually applicable. Lange (1965) has, however, detected lava tubes by magnetic means.

A method, not fitting into the general scheme, but widely used by the Americans, consists of a microwave (infra-red) thermometer flown at night which can detect old mine roadways beneath highways (Letheren 1972).

Editor's comment: The authors have here presented a summary of geophysical experiments which need following up, though their personal circumstances make this difficult. Many others are known to have conducted experiments which have been published and it is hoped that the contribution herein will stimulate those people, and anyone else, into completing their tests and presenting them to all speleo-geophysicists. Only by a full collation of results will we arrive at a sound method of remote detection of caves, and thereby prevent unnecessary duplication of effort. By coincidence an American Army report on this subject has just reached the editor as the Transactions goes to press. It is "Detection of subsurface cavities" by E.R. Bates, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. June, 1973. approx 100 pages. Amongst his conclusions the author says that a modified Bristow method holds out most promise. It is hoped to present a review in B.C.R.A. Bulletin shortly.

Electrical Resistivity Methods

Every caver dreams of a technique to assess the potential of a "dig" before commencing often unrewarding back-breaking labours. Electrical resistivity surveying is unlikely to provide an easy answer but given the right conditions may provide useful information e.g.,

(a) Quantity of fill and the shape of swallow holes beneath the fill. (Cook & Von Nostrand 1954).
(b) Thickness of overburden.
(c) Depth of near-surface cavities.

Three different resisivity techniques have been tried at what were regarded as progressively simpler locations; these were the Wenner Depth Probe, the Wenner Traverse and the Single Electrode Probe technique of Bristow (1966). Only the last appears to have much potential for cave detection.

The Wenner Depth Probe

Depth probing is a technique whereby the electrode spacing is progressively increased from a fixed centre, deeper and deeper current paths being investigated. The Wenner array, utilising equidistant electrode spacings allows computations to be simplified (Palmer 1954; Wilcock 1965).

A depth probe about 20m. above the surveyed position of Mitchell's Cavern (Pikedaw Calamine Caverns, Malham, Yorkshire) seemed to indicate complete screening of cavities by the associated base metal mineralisation, a low resistance anomaly being detected rather than the expected high resistance anomaly of an air-filled cavity.

The method has been used by Palmer (1954) with a measure of success, and the accurate location, in 1956, of the entrance and passages of Pen Park Hole, Bristol was a prime example. (Tratman 1963). Palmer concluded that a reasonably large cavity not too far from the surface could be located with some precision but details of size and shape were much less reliable.

Consideration of Maxwell's laws of images enables expressions to be derived for a spherical cavity in a homogeneous medium. The theory can be readily found in Tagg (1964) or Palmer (1954).

Fig. 1 shows the theoretical anomaly for a spherical cavity in a homogeneous medium. Equating the first differential to zero locates the position of the bulge:—

$$h = \sqrt{\alpha y_0} = 0.58 y_0 \text{ (for the Wenner array).}$$

where α is the ratio $\frac{x}{y}$, x being half the potential electrode separation and y half the current electrode separation. y_0 is the electrode spacing at the maximum apparent resistivity ρ (Fig. 1.).

Theory predicts the magnitude of the bulge on the high resistance side of the straight line to be:—

(a) Proportional to $\left(\frac{r}{h}\right)^3$ for point electrodes and a spherical cavity.

(b) Proportional to $\left(\frac{r}{h}\right)^2$ for a horizontal 2-dimensional discontinuity i.e., a tunnel,

where r is the cavity radius and h the distance from its centre to the surface.

For a good anomaly r should be large and h small.

Palmer (1954) produced 3 experimental graphs showing the effect of a railway tunnel in a 2-layer medium. Repeated measurements were made on the same traverse for different α with the electrode array centred above the tunnel. The anomaly was bracketed above and below by low resistance kinks which Palmer accounted for as either accumulations of water above the roof or the effect of metal rails. The value of y_0 (spacing at ρ max.) for the anomaly decreased as α increased but according to theory $\sqrt{\alpha y_0}$ = constant = depth of the tunnel. However, the mean depth was close to the actual tunnel depth. The magnitude of the bulge showed no correspondence with theory.

The magnitude of the anomaly as measured is likely to be subject to considerable fluctuations depending on electrode contacts, generator voltage and ground effects whereas the depth determination depends on easily measured electrode spacings and is likely to be reasonably accurate.

However, Palmer developed his technique on carefully chosen sites. In practice the areas of interest are invariably far from ideal. A high resistance bulge may still indicate a cavity but the calculation of depth becomes more a matter of "guesstimation".

The site chosen for a test was in Bullpot Valley (Casterton Fell) above "Burnett's Great Cavern" (Bullpot of the Witches). Using the Megger earth resistance meter, a Wenner depth probe was carried out and corrections for potential electrode resistances made. Similar experiments were made at this location by Wilcock prior to the Oxford University expedition to Northern Spain in 1961 (Wilcock 1963, 1965). The resistivity curve (fig. 3) shows a slight bulge at B. The fluctuation indicates a rapid increase in resistivity perhaps due to an air cavity effectively increasing the current path considerably for a relatively small increase in electrode spacing. The top of Burnett's chamber is about 9 metres below the surface and its volume is of the order $1 \times 10^4 m^3$. Considering these quantities the anomaly measured was disappointingly small.

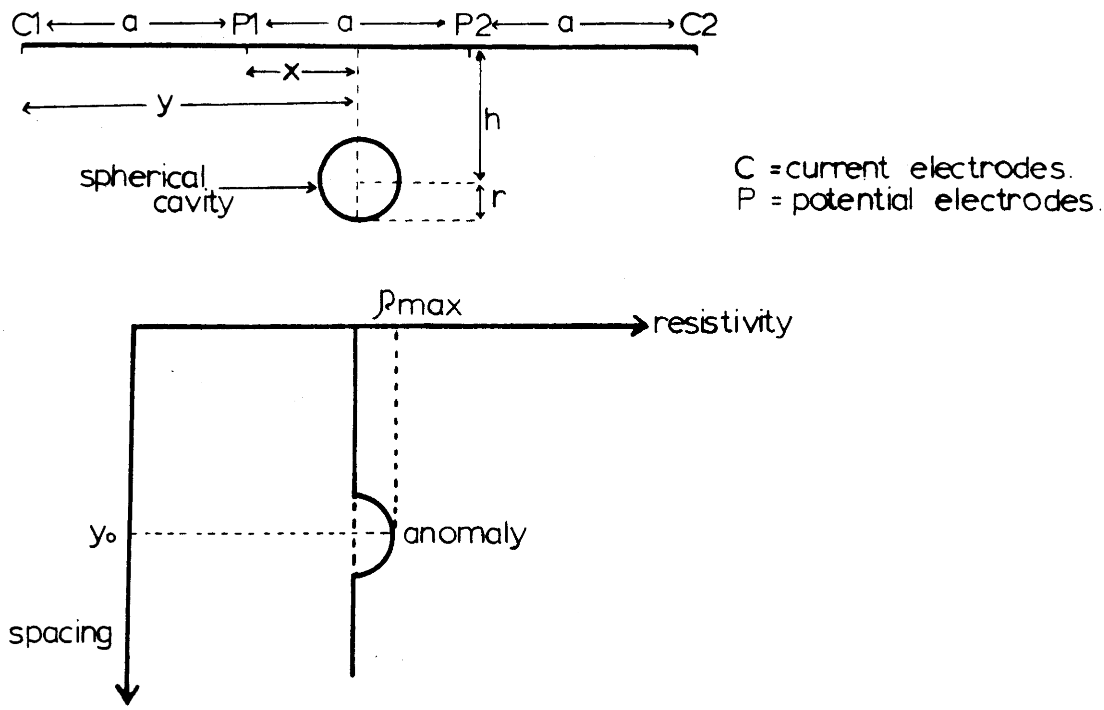
The exercise was conducted in a moderately complex area approaching the Dent Fault. The probe did not cross any known faults and the electrode spread was arranged parallel to the strike. Near the fault the joints in the limestone tend to be accentuated and the dip increases rapidly so overall a directional homogeneity with respect to resistivity was expected and the problem to be that of two layers i.e. drift/limestone. The graph shows the variations to be far from ideal and beyond the reach of simple 2-layer curve matching.

Wenner Traverse

Given the depth of a cavity a traverse can be made using a fixed electrode spread. The maximum anomaly due to a cavity is expected on crossing a tunnel with the array parallel to the strike.

THEORY.

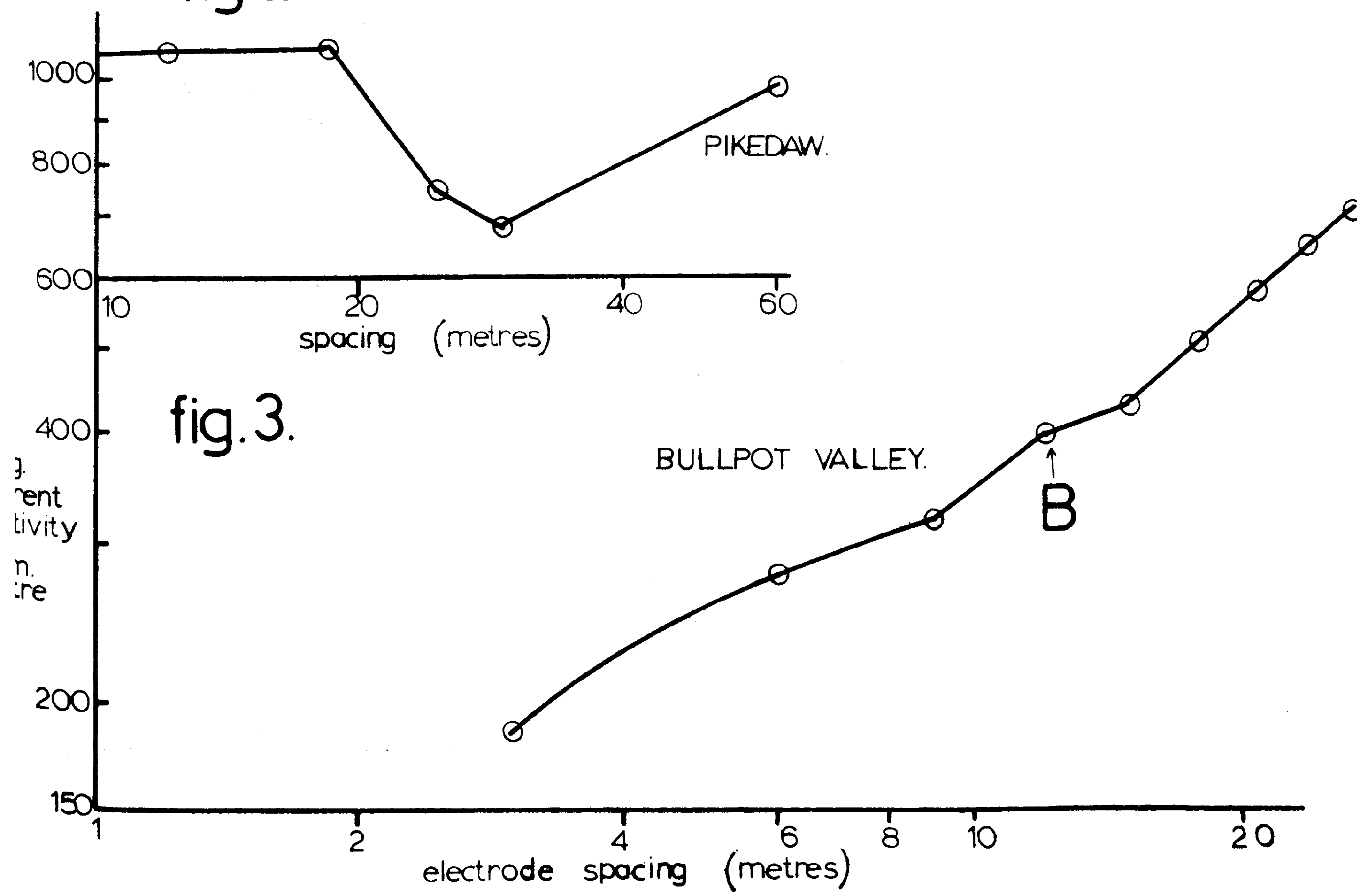
ig.1. Wenner depth probe.



DEPTH PROBES.

fig.2.

fig.3.



WENNER TRAVERSE.

Upper Long Churn.

fig. 4.

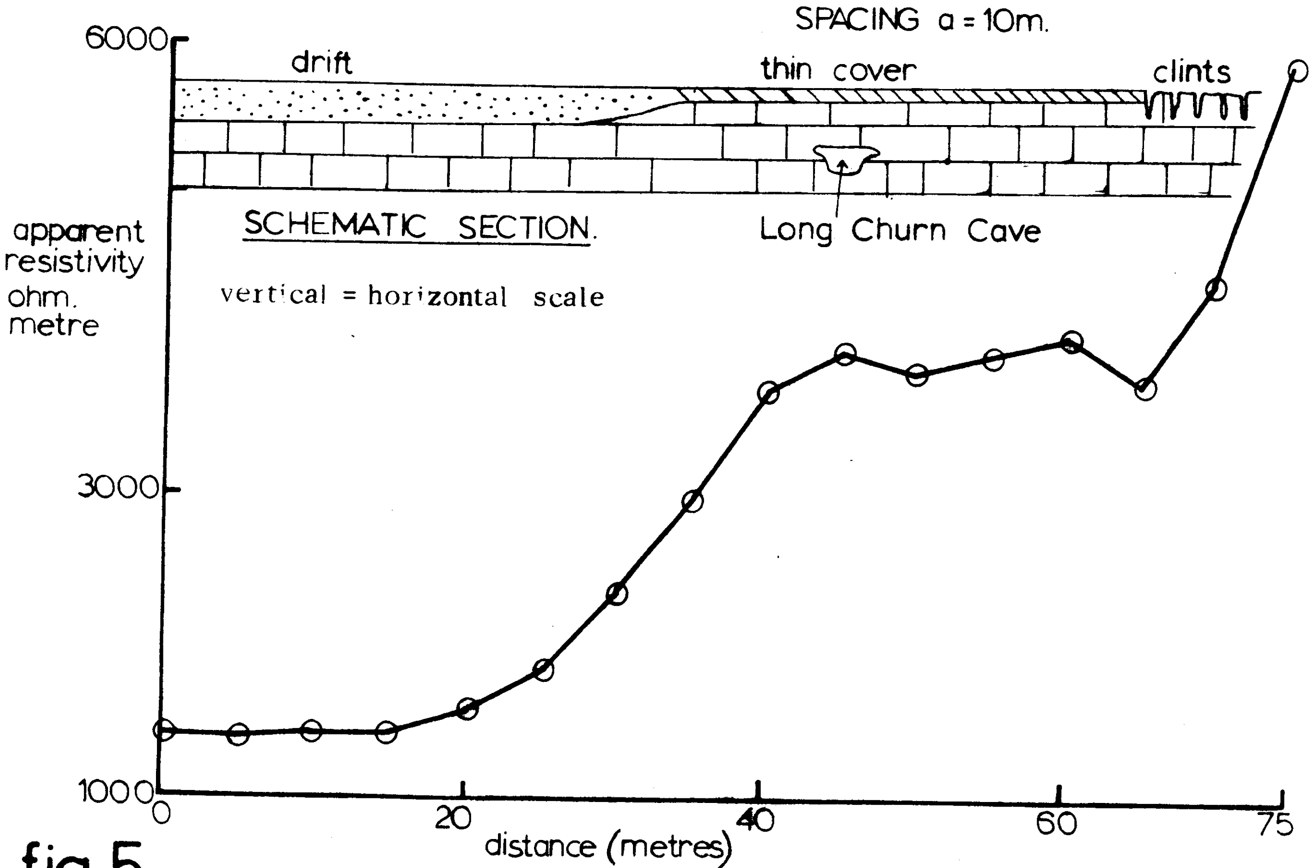
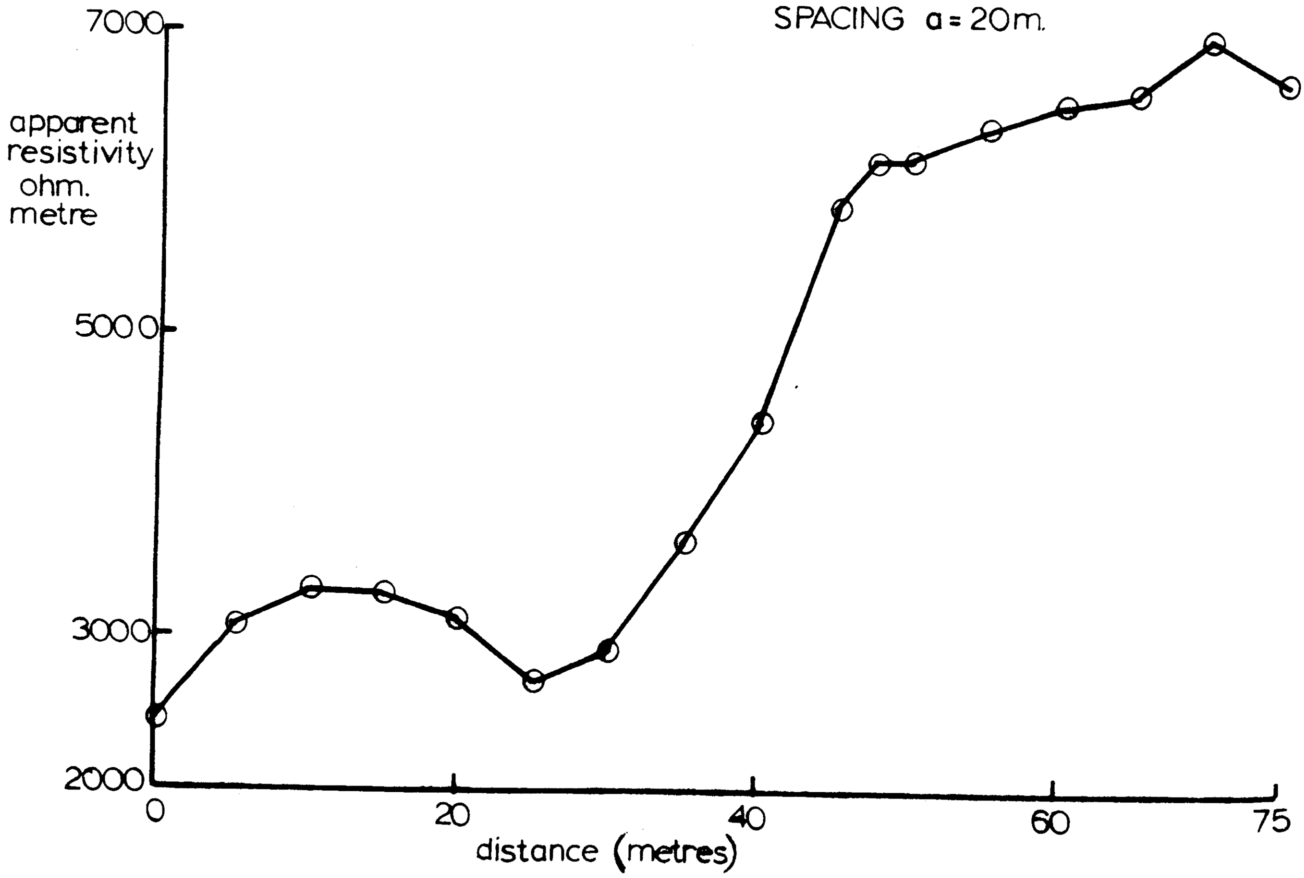


fig. 5.



Upper Long Churn (Alum Pot area) was selected for the experiment. 20 and 10m electrode spacings were tried but no clear anomaly was detected. Figs. 4 and 5 show a low apparent resistivity on a waterlogged drift covered area, increasing on the thinner limestone soils and even further on the clints. Where thin cover and bare rock persists there is difficulty obtaining a measurably low electrode resistance. The earth may need to be dampened by any water immediately to hand.

It can be concluded that classical resistivity techniques do not lend themselves to detecting these two underground cavities, so a further technique was tried in a more simple and better known locality.

The Single Electrode Probe Technique (after Bristow 1966)

One of the current electrodes is used as a central electrode and the other is placed theoretically at infinity, but in practice at several decametres. The potential electrodes are moved as a pair with constant separation, from the central toward the infinity electrode along a line between the two (Fig. 6).

The theorty of the method is based on the assumption that the equipotential surfaces around the current electrode are hemispherical. This is probably approximated if the "infinity electrode" is distant enough to prevent distortion and the ground is reasonably homogeneous. The potential electrodes measure the potential drop across individual potential bowls. If the ground beneath the traverse is uniform, the resistivity of individual bowls is a function of the distance from the central current electrode to the potential electrodes (see equation (I)). However if one or more of the bowls intersects a cavity, then the resistance and the calculated resistivity of the bowls is increased.

The resistivity ρ of the ground enclosed by two bowls is calculated as follows:—

Let dr be the small difference in radius and dR the small difference in resistance between a pair of equipotentials.

Now resistance can be defined $R = \frac{\rho l}{A}$

where l = length under consideration.
A = cross-sectional area.

Applying this to the case in question

$$dR = \frac{\rho dr}{2\pi r^2}$$

$$R = \int_b^a \frac{\rho dr}{2\pi r^2}$$

where a = radius of an equipotential bowl.
b = radius of the adjacent bowl, $b < a$.

Integrating gives $R = \frac{2\pi a.b.R}{(a - b)}$ (I)

From this equation the apparent resistivity is calculated from a measured apparent resistance by multiplying by a factor which is a function of the distance of the potential electrodes from the central current electrode.

A series of apparent resistivity values is obtained along the traverse, the position of the current electrodes altered, and a traverse made in the opposite direction (Fig. 7).

The method described above was used over Batty Wife Cave, Ribblehead, Yorkshire. A line angled at about 30° to the trend of the passage was traversed. The distance between the two current electrodes was 50m for both traverses. The greatest current electrode separation (CIA to CIB or C2A to C2B on Fig. 7) giving significant meter deflections is used. This distance is limited by such factors as ground saturation and the power of the electrical supply. Apparent resistance readings were noted for the two traverses in opposite directions and the apparent resistivities calculated from equation (I). These values were plotted and interpreted as cavities (Fig. 8).

Comparing the predicted cavities with the actual position and extent of Batty Wife Cave, it can be seen that they are considerably larger than the cave itself. The sizes of the predicted cavities have been estimated from the intersections of the hemi-spherical bowls. These cavities are possibly enlarged bedding planes which intersect the cave. In fact, water can be seen issuing from a bedding plane at the base of the southern wall of the cave and also from the stream bank just outside the cave. Needless to say the experiment was carried out during heavy rain. The interpretation has not yet been substantiated by further traverses in the area.

The method shows some promise although the well-defined anomalies may be due to the shallow depth of the cave compared with the other tests and it is unfortunate that time was not available for testing the other methods on the same site.

The single electrode method has several advantages:

(a) For a significant anomaly the authors consider the few percent electrode resistance correction to be negligible so the readings can be immediately plotted in the field and a cave passage traced out on the ground. Bristow records considerable success with the method. It must be remembered that with multi-layer problems the equipotentials are no longer represented by hemispherical bowls so compass drawn intersections will not give the true depth.

fig.6.

THEORY.

The single electrode method.

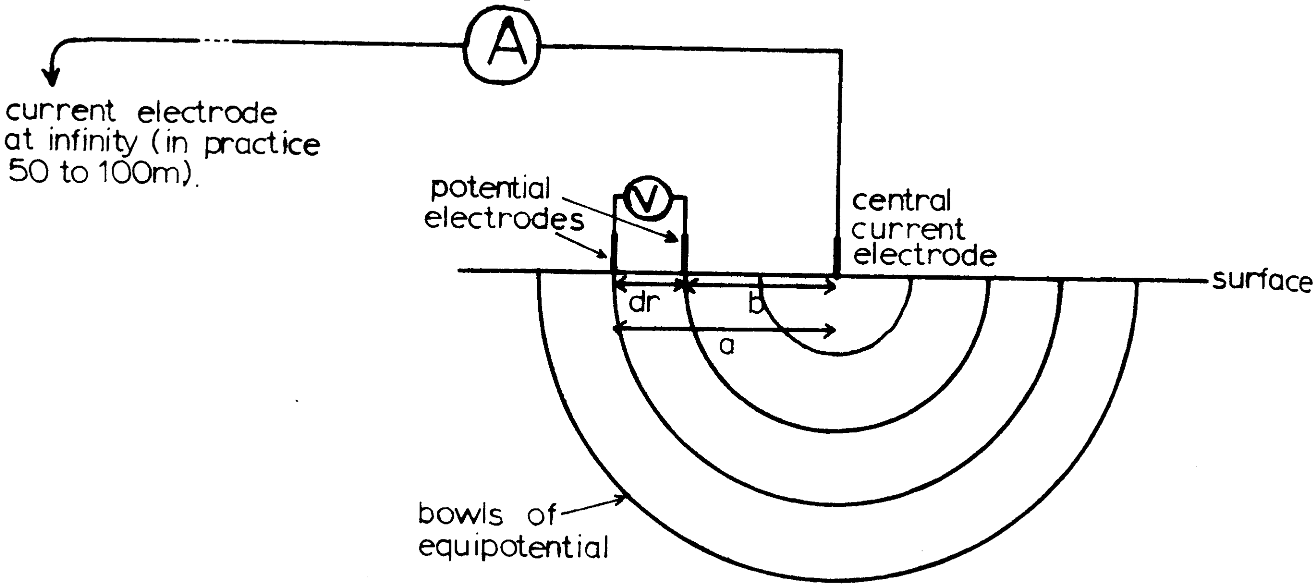


fig.7.

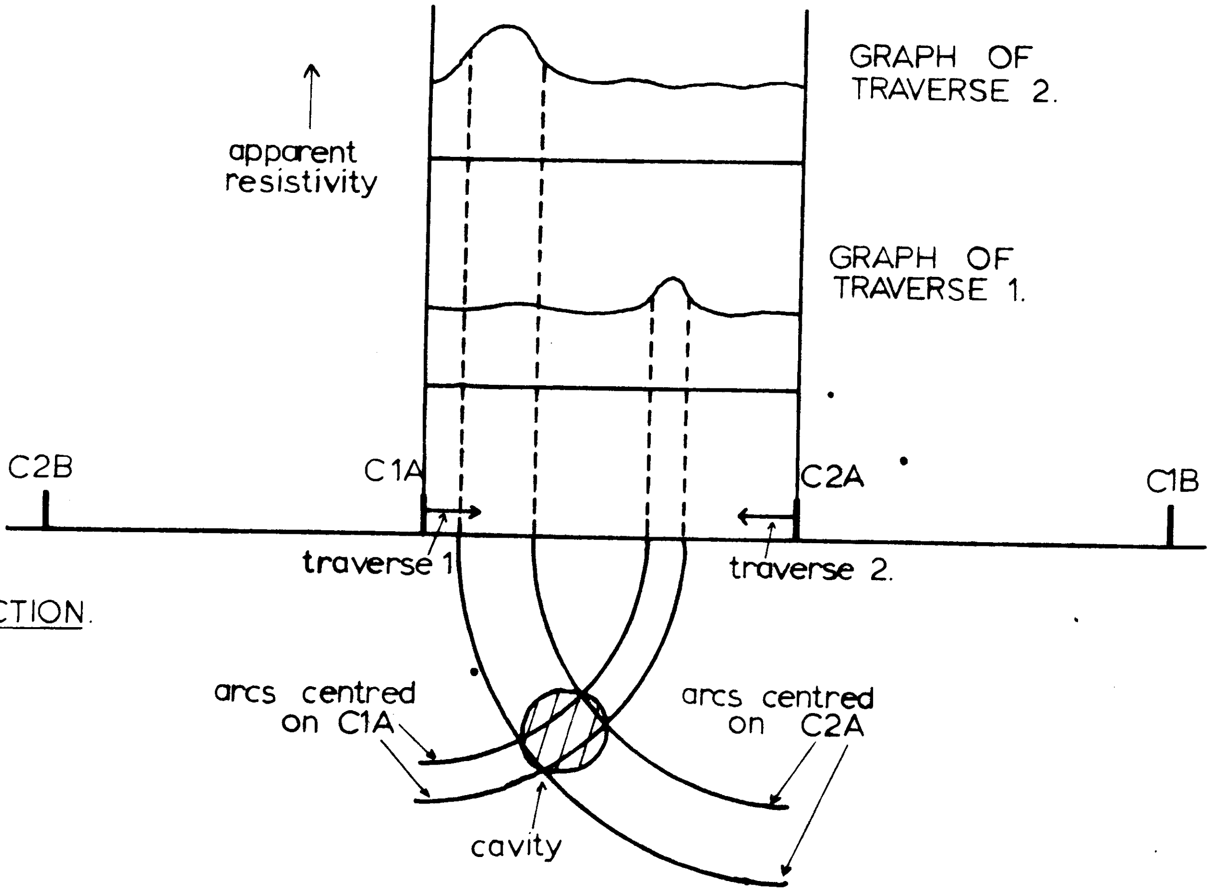
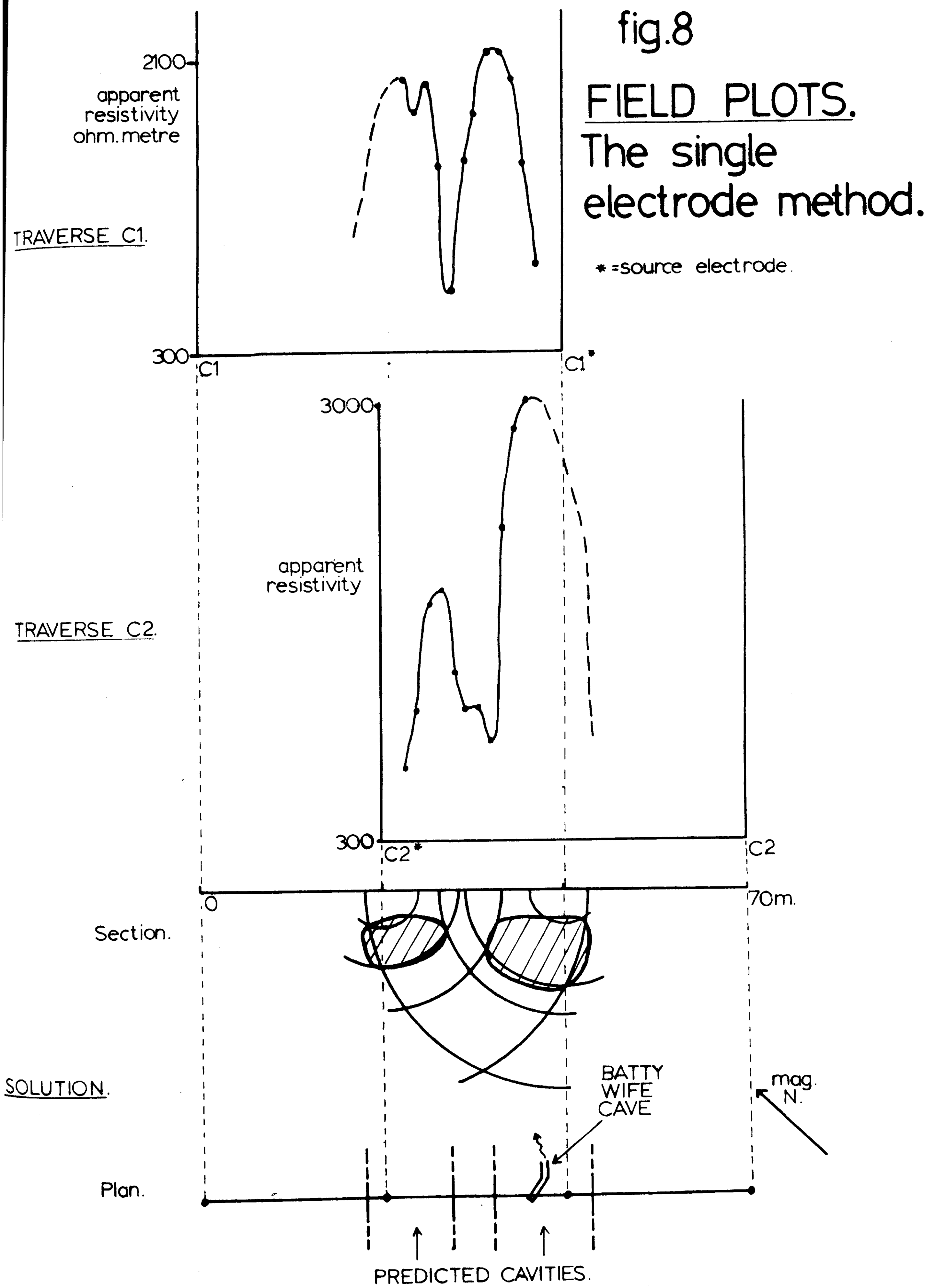


fig.8

FIELD PLOTS.

The single electrode method.



(b) A fixed length of cable between the potential electrodes enables each traverse to be completed rapidly. A mark in the centre of the fixed spread locates the next station i.e. readings are made at intervals equal to half the potential electrode separation.

When using the Wenner system occasional readings were checked and lateral homogeneity confirmed by using the tri-potential method (Carpenter & Habberjam 1956) i.e.

The electrode layout CPPC (as generally used) measures apparent resistance $R\alpha$

CCPP measures apparent resistance $R\beta$

CPCP measures apparent resistance $R\gamma$

It can be shown that $R\alpha = R\beta + R\gamma$. Agreement should be within ±3%.

Conclusions

The results so far indicate severe limitations on the use of resistivity methods. In geologically simple areas the single electrode technique may prove the most satisfactory for remote cavern detection. At present the second author is developing some lightweight equipment in order to pursue resistivity methods further.

J.O. Myers has suggested a modification whereby one electrode is placed in a sinking stream to which salt is added to enable low resistance flooded passages to be traced.

Acknowledgements

We express grateful thanks to D. Coney, S. Crabtree, A. Latham, D. Hodgson for invaluable assistance and to Dr. J.O. Myers (Dept. of Mining and Min. Science, University of Leeds) for advice and the loan of equipment.

Revised M.S. Received 1st October, 1974

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A HISTORY OF KARST STUDIES IN YORKSHIRE

R. A. Halliwell.

Abstract

This paper traces the development of limestone studies in the Yorkshire Dales concentrating mainly on sub-surface and hydrologically oriented studies. A chronological bibliography of important historical papers is included.

1. Introduction

The historical approach to the changing concepts of speleogenesis has been summarised by several authors, who all approached the subject from a world wide viewpoint. (Herak & Stringfield, 1972; Shaw, 1974; Sweeting, 1973). This paper attempts to trace a similar growth in limestone studies with particular reference to the Yorkshire Dales limestone area.

As an aid to tracing changes the ideas are described in three independent sections, hydrology, cave studies and surface studies; however it must be remembered that the three are intimately linked.

2. Karst Hydrology

The earliest reference to limestone hydrology in Yorkshire is possibly that contained in Drayton's Poly-olbion (1613-22) which describes the Ebbing and Flowing Well at Giggleswick.

"At Giggleswick where I a fountain can you show,
That eight times in a day is said to ebb and flow!"

This well is also mentioned by Speed (1672) and Cox (1720-31) although neither mentioned any other features of the limestone scenery in the Yorkshire Dales. On a larger scale possibly the first written description of caves and underground water flow was that given by Pococke (1751), who in his description of the river Greta in Chapel-le-Dale assumed that the subsurface flow followed the course of the dry surface river bed. In his description of "Weather Coat Cave" he mentioned that "this whole cavern has been sometimes full of water, and run over"; whilst at "Jardours Cave" [Yordas Cave] as well as inspecting the interior of the cave he "went up the hill, over it, and saw the stream come rushing down . . . it is lost in the ground near the place where we saw it come out in the cave". At Malham Tarn "the water runs out in a rivulet, which soon divides into two parts, and is lost among the stones, going underground by what they call two swallows . . . and these streams from the Pond are supposed to come out from the east of Malham, where the river Aire comes from under the mountains. Going about a mile to the south we come to what they call Malham Cove.... At the bottom of it a rivulet comes from underground supposed to be made by the swallows on the moors". A little later he continued "We went again to Malham and saw what is called the real rise of the Aire, very near that village. There are two springs called the Upper Head and Lower Head which soon meet. The other two which fall into it are Cove Beck which comes from the Cove, and Gordell Beck.... We passed by the remarkable Swallows from the Malham Tarne, which have been found to be the sources of the Upper and Lower Heads". Thus over two hundred years ago the hydrology of the Malham Tarn area was realised to be more complex than the surface features suggest.

This awareness of underground drainage directions, although again no reasons are given, was demonstrated by Hutton (1761) "There is also another called Gaper Gill, into which a good many springs fall in one stream, and after a subterraneous passage of upwards of a mile, break out again and wind through Clapham". In the 1781 edition of "A Tour to the Caves" Hutton writing on the streams flowing from Hull Pot to Douk Gill Scar and Hunt Pot to Bransgill Head remarked "But what is most extraordinary, these subterranean brooks cross each other underground without mixing waters, the bed of one being on a stratum above the other: This was discovered by the muddy water after a sheep washing, going down the one passage, and the seeds or husks of oats that were sent down the other." This comment is important, not only because it recognised the fact that limestone streams flow underground in discrete channels, but also because it indicated a deliberate attempt at water tracing. Although holding unusual ideas on cave origins Hutton stated a second important hydrological principle, "the springs were entirely dependent on the rain; were dried up in a drought; very fluent in wet weather".

Shortly after Hutton's book several other descriptions of Yorkshire limestone features were published although none approach the significance of Hutton (Bray 1783; Hurtley 1786; Byng 1792). A pamphlet by "A Gentleman of the University of Oxford" (1798) is of more interest because it mentioned the first analysis of limestone spring water "Pass a spring, called the Light Water Well, which has its name from its waters having been found lighter, than any other springs, in this vicinity, by an ingenious apothecary, of Ingleton, who made experiments on them".

The writings of Houseman (1808) could be taken as representative of the initiation of more scientific studies, in addition to describing several caves he set forth detailed measurements of water levels at the Ebbing and Flowing Well, Giggleswick and further suggested that the ebb and flow mechanism might be representative of antecedent weather conditions. These measurements are important because they appear to represent the first attempt at the quantification of limestone hydrology. Other papers containing detailed discharge measurements at this point followed (Whitaker 1812; Gough 1813).

Following this initial period of rapid development of ideas and study, there was a period when very little work on limestone hydrology was initiated. Hughes (1887) gave a very detailed description of the great flood of 1872 but produced few new ideas on limestone hydrology. The next major development took place at the beginning of the twentieth century with the pioneering work of the members of the

Yorkshire Geological Society, who established a large scale programme of underground water tracing, initially in the Malham area and then around Ingleborough. The methods used included artificial flood pulses, salt, ammonium sulphate, methylene blue and fluorescein, but as time progressed only the latter method was used because it was "by far the most useful and trustworthy". This work is important not only because it established underground routes but also because it demonstrated variability of flow-through time with general hydrological conditions, both preceding and during the actual test. The results of the tests were published by Carter & Cash (1900), and Carter & Dwerryhouse (1905) together with the chemical analyses of the waters of the Malham Tarn area, and the major tracings were also listed in a pamphlet by Brown (1906). These activities were in conjunction with a British Association Committee which issued brief annual reports over the same period.

After this active period there was again a scarcity of new studies. Strahan (1910) recognised the geological control on springs stating that the majority of them occurred "on reaching an impervious strata". He also stressed "how totally independent are the open air and the underground courses" of the streams. Baker (1932) and Mitchell (1937) both compared flood and drought conditions in caves but a paper by Aspin and Leach (1954) may be said to mark the resurgence of interest in dye-testing. Their work is of value not only because of the description and result of the trace, but also because of the detailed discussion of weather conditions and throughflow times. They also suggest the possibility of the slow transmission of dye through an underground reservoir, "moving along quite slowly until pushed out 'vis a tergo' supplied by the entry of flood water into the system". This concept was considerable studied and expanded by Ashton (1965) in generating his ideas of flood pulse analysis. His type of analysis has been used to predict the nature of cave passages which are inaccessible because of flooded regions.

Another type of limestone hydrology study which was becoming increasingly common during this time was work on limestone water chemistry. In 1965 Richardson produced a paper directed at Yorkshire cavers, attempting to persuade them to collect water samples, and in 1968 he wrote about "The use of chemical analysis of cave waters as a method of water tracing and indication of the type of strata traversed". This paper is an attempt to relate the limestone water characteristics to the type of underground flow feeding the spring or resurgence under study. Also in this year Pitty (1968) attempted to relate the calcium content of limestone waters to their throughflow period and the antecedent temperature conditions. Similar work by Ternan (1972) on limestone springs suggested using the variation of calcium hardness as a method of differentiating springs from resurgences.

The majority of work on limestone water chemistry which has been undertaken in recent years in Yorkshire is collected together in 'Limestone and caves of north-west England' (Waltham, 1974). The results of hydrochemical research in three classic Yorkshire cave systems have been described therein: Halliwell reported work on the effects on inlets on the main cave streamway in Swinsto, Pitty described work on throughflow times of seepage flows in Ingleborough Cavern, and Richardson provided a detailed analysis of water hardness measurements in the Alum Pot area. These studies are also important because they include discharge measurements. Many cavers know the way cave streams can vary in size but few have made any measurements of water flow. The chapter by Ternan shows that not only is there an inverse relationship between hardness and discharge as found in the other limestone areas of Britain but also that the relationship is much stronger and the dilution peaks appear to pass through the caves more quickly.

3. Sub-surface studies

The descriptions of caves given by Pococke (1751) and Hutton (1761) were followed by those of Defoe (1778), Walker (1779) and Dixon (1781). However it was probably not until 1781 that the first book solely devoted to Yorkshire caves was produced, Hutton's "A Tour to the Caves". The descriptions contained in this book are quoted in many later guides to the area, both with and without acknowledgement, and this usage of the book has been studied by Shaw (1971). The book was intended as a guide for visitors and this increasing popularity of the limestone countryside as a general tourist attraction is demonstrated by Westall's book of engravings "Views of the Caves near Ingleton, Gordale Scar and Malham Cove in Yorkshire" (1818). This publication also contains some precise descriptions of flood damage to Yordas Cave, and of water flowing over Malham Cover after heavy storms.

The period from 1830 onwards was a very important one in the development of cave studies. Much work was done, with an archaeological bias, in the study of cave sediments. It is also at this time that Farrer was in the process of surveying Ingleborough Cave, although the completed survey was not published until 1848. In 1847 and again in 1848 Birkbeck attempted to make the first descent of a major Yorkshire pothole, Alum Pot via Long Churn Cave. "The party consisting of ten persons, ventured into this awful chasm with no other apparatus than ropes, planks, a turn-tree, and a fire-escape belt" (Dawkins 1874). Phillips (1855) in his book "Rivers, Mountains and Sea Coast of Yorkshire" made use of information from these caving expeditions to demonstrate several important factors affecting limestone erosion, namely, the effect of jointing on cave passage directions, "the corrosive action of streams of acidulated water", and mechanical erosion "by sand and pebbles". Dawkins' book also contains an appendix with the accurate measurements taken in Ingleborough Cave to demonstrate the rate of growth of stalagmites.

In a paper given to the Manchester Geological Society in 1871 Dawkins stressed that the presence of a vegetation cover increases the amount of carbon dioxide in the soil and thus considerably speeds up the rate of limestone solution. In the discussion following the meeting E.W. Binney suggested that the cover might also be important because it could lead to the production of "vegetable acids" as well as increasing soil carbon dioxide. This paper is important because it marks the primary recognition of the implications of a vegetation cover in any study of a limestone region.

Three years later Dawkins (1874) produced "Cave Hunting" the first book in English devoted entirely to cave science. Although much of the book is concerned with archaeology there is a considerable section explaining the erosional enlargement of limestone caves.

> "The work of carbonic acid is provided not merely by the acid-worn surfaces of the interior of the caves, but also by the large quantity of carbonate of lime which is carried away by the water in solution. That, on the other hand, of the mechanical friction of the stones and sand against the sides and bottom of the water courses, is sufficiently demonstrated by the grooved, scratched and polished surfaces and by the sand, silt and gravel carried along by the currents. The generally received hypothesis, that they have been the result of a subterranean convolusion, is disproved by the floor and roof being formed, in nearly every case, of solid rock; for it would be unreasonable to hold that any subterranean force could act from below, in such a manner as to hollow out the complicated and branching passages, at different levels, without affecting the whole mass of the rock. Nor is there cause for holding the view put forth by M. Desnoyens or M. Dupont that they are the result of the passage of hydrothermal waters. The causes at present at work, operating through long periods of time, offer a reasonable explanation of their existence in every limestone district; and those which are no longer water courses can generally be proved to have been formerly traversed by running water, by the silt, sand and rounded pebbles which they contain. In their case either the drainage of the district has been changes by the upheaval or depression of the rock, or the streams have searched out for themselves a passage at a lower level."

Like Phillips he used Farrer's measurements of stalagmite growth in Ingleborough Cave but he compared these with his own measurements collected in 1873 from which he obtained a different rate of growth. Using this variation he concluded "that the thickness of layers of stalagmite cannot be used as an argument in support of the remote age of the strata below". When discussing Alum Pot he also suggested that "the absence of stalactites and stalagmites proves that the destructive action is rapidly going on".

This latter concept was also recognised by Bird (1881) who suggested that fossil cave systems which have been deserted by water will contain a prolific display of formations as compared with active cave streams; for an example he quoted Ingleborough Cave. Bird's book also attempted to explain the chemistry of limestone solution and suggested that it may be demonstrated experimentally using lime water. He did, however, recognise that a considerable portion of erosive cave development is due to mechanical action.

"On Caves" by Hughes (1887) continued this theme and went further by suggesting a sequence of chemical cave formation followed by a period of both chemical and mechanical cave development, thus recognising two distinct stages in the history of a cave. This paper is also of interest because of details it gives of the great flood of 1872. Large volumes of Yoredale debris were transported completely through the Gaping Gill-Ingleborough Cave system to Clapham Beck during just one storm and the farther reaches of Ingleborough Cave were considerably altered.

Concurrent with these changing scientific ideas there were great advances in cave exploration. In 1870 Birkbeck and twelve others "including three ladies" finally reached the sump at the bottom of Alum Pot. "The apparatus employed consisted of a windlass supported on two baulks of timber, and a bucket, covered with a shield, sufficiently large to hold two people, and two guiding ropes to prevent the revolution of the bucket in mid-air. There was also a party of navvies to look after the mechanical contrivances, and two ladders about eight feet long to provide for contingencies at the bottom". An unsuccessful attempt was made by Birkbeck in 1872 to get to the bottom of Gaping Gill although he did reach the ledge 190ft below the surface. The increased interest in exploration is demonstrated by the first major cave guide book to be published after Hutton (Balderston 1888), which included a detailed map locating a large number of cave entrances. This was closely followed by further descriptions in Speight's book (1892) "The Craven and North West Yorkshire Highlands".

In the same year the Yorkshire Ramblers' Club was formed with some of the aims and objects of the club being '"... to organise walking and mountaineering excursions and to gather and promote knowledge concerning Natural History". In spite of there being no mention of caves, the first Annual Meet visited Yordas Cave and in 1895 the Annual Report stated "...during the year substantial progress has been made in the exploration of Yorkshire's caves and potholes". It was also in this year that the club were thwarted in their attempt to achieve the first descent of Gaping Gill. Martel reached the floor of the Main Chamber on August 1st 1895 but was unable to explore any of the system outside the Main Chamber. His own description of this historic descent and much other hydrological data is contained in his book "Irlande et Cavernes Anglaises" (1897). In this year Cuttriss and other members of the Yorkshire Ramblers' Club prepared the first accurate survey of a Yorkshire pothole (as opposed to Farrer's 1848 Ingleborough Cave Survey) and during the making of this survey of Rowten Pot a certain amount of scientific work was undertaken:

> "On reaching the bottom of the pot, Cuttriss — always accompanied with that mysterious green rucksack of his — busied himself with chipping off bits of rock and taking the temperature of the air and water, but I could not for the life of me see why in doing this, he should consider it necessary to stand up to his knees in water for ten minutes or so, with a thermometer dangling by a bit of string from a button on his coat. The compass and barometer, too, has to be consulted."

Writing in the Club Journal about cave origins, Cuttriss (1899) recognised the need for an impervious caprock in order to concentrate rainfall and produce swallet streams rather than all the rainfall sinking as percolation water. Lowe (1903) also writing in the Club Journal stated that although the sequence of cave development is understood, "a satisfactory explanation of an earlier condition of limestone, when the minute cracks and fissures were in the process of being enlarged, is still wanting". He also quoted Dwerryhouse, "It may be confidently said that there is a general parallelism between joints and passages but this is by no means as close as was at first expected", and continues to explain these deviations in terms of down-dip and cross-joint passages. Although there was general agreement over the processes of cave development the Club members did manage to find some exceptions (Brodrick 1905) to the accepted ideas which were summarised by Dwerryhouse in 1907.

In 1910 Strahan reiterated the ideas of Bonney "that limestone is soluble in acidulated water, such for example as has picked up vegetable acids in its passage through the soil". Kendall and Wroot (1924) noted the increased acidity of water due to soil carbon dioxide formed beneath an overlying vegetation cover, but they also admitted the possibility of additional erosion due to organic acids. Also whilst admitting that master joints, generally trending north-north-west to south-south-east, would produce an overall cave direction, they suggested that the more detailed morphology, in terms of meanders, ox-bows and the like, can be directly compared to surface streams and that the causal factors are identical. Wager's paper (1931) is entirely geological in approach but is important because of the already much stressed relationship between joints and cave passage directions, in fact Warwick (1962) stated "a study of Wager's paper is necessary for an understanding of cave formation and development".

In the two decades from 1910, although the Yorkshire Ramblers' Club was very active in terms of cave exploration, no significant work of a cave science nature was undertaken. The position did, however, change in the 1930's with Baker's (1932) book on cave exploration containing a comparison of caves in flood and drought, as does Mitchell's book (1937). 1935 marked the formation of the British Speleological Association with one of the Association's objects being "the co-ordination of the results of research in all matters affecting the study of caves".

This year also saw the publication of a paper by Simpson "Notes on the formation of Yorkshire Caves and Potholes". Forty years previously Tiddeman had defined a scarcity of shale beds as an important factor in cave origin, now Simpson continued "another important factor, responsible for the joining up step by step, fracture by fracture, is cave formation in the Shale Beds... Swinsto Cave... offers an even more interesting illustration of the part that shale beds play in directing the underground flow of water . . . We were able to trace six shale beds in Swinsto Cave and in four of them they form the flat roof of the communicating passage which joins up the vertical fissures or fractures". In many of the Yorkshire cave descriptions which followed this general paper the important part played by shale bands was noted (Grainger 1938, Simpson 1948, Atkinson 1949, 1950). Myers (1948) expanded the concept a little further stating "In many cases, however, a passage has started as a low opening on a thin shale bed in the limestone and has cut down into the limestone below ... the majority of Yorkshire caves appear to be of vadose origin". Sweeting (1950) although mentioning the importance of shale bands did not entirely follow this concept but developed an idea of Hudson (1933) that "the successive pitches show evidence of a series of water tables", and attempted to link common passage levels to possible fossil water table levels, thus opposing Myers by suggesting a shallow phreatic origin.

Simpson's general concept remained dormant in the decade following Sweeting's paper, but re-emerged recently with Waltham (1970) restating the main axioms that "Together with joints and faults the dominant controls of cave development are the shale beds. The early downward drainage of the limestone was always collected and flowed on these shales until they could drop through them down a joint. Efficient and concentrated stream flow then rapidly eroded the shale and the main passage enlargement took place in the limestone, immediately below the shale in the vadose environment". Throughout the paper the fact that the simple terms vadose and phreatic are insufficient to describe cave development is stressed, many caves in fact show features of both types. "The present more detailed studies of the caves show that the generally small simple caves form integral parts of the adjacent major cave systems." This paper is criticised by Brook (1971) who, instead of Waltham's modified Bretz-Davis model, proposed a shallow phreatic/epiphreatic model based on temporary perched "saturation-zones".

Waltham's book (1974) contains a general introduction to cave geomorphology and describes examples of several speleogenetically diagnostic types of cave features. These features were used by Waltham and other authors in the book to produce suggested cave chronologies with a number of phases of cave development, separated and ordered and in some cases tentatively linked to glacial sequences. The book also contains detailed geological and hydrological descriptions of most of the classic caving areas of Yorkshire and the inter-relationship of these variables within the caves. Glover's chapter on Gaping Gill (in Waltham 1974) draws attention to the close lithological control of passage development exercised by the Porcellanous Band and an aven development by faults and major joints. His arguments have recently been extended in two contributions to the Craven Pothole Club Journal (Glover 1973, 1974).

4. Surface Studies

Although many of the early descriptions of Yorkshire mention the unusual limestone landforms it is probably that the first essentially scientific book describing the Yorkshire karst features is Phillips' "Illustrations of the geology of Yorkshire: the mountain limestones" (1835). Much of the work following this time has already been described; however additional descriptions of the geology of the area include

Dakyns (1890), and McKenny-Hughes (1900), who recognised the significance of the concentric lines of shakeholes around Ingleborough as suggesting a retreat of the overlying impervious caprock. In 1924 Kendall and Wroot attempted to link surface and sub-surface features by suggesting that gorges, such as Trowgill, are due to cavern collapse. Moseley (1955) also attempted this link by extending the importance of shale bands in cave formation to include an effect on surface features and "suggested that the thin shale bands between successive layers of horizontal limestone have helped both to form limestone pavements by limiting the downward penetration of water and to strip off individual layers at their edges by a sapping effect" (summary by Warwick 1962).

The many semi-horizontal surfaces of the West Yorkshire Dales and the general landscape features of this area were the subject of much argument in the early fifties between Corbel, Ford, Moseley and Sweeting (1951-52).

On a smaller scale in terms of landscape features, Jones (1957) produced a thesis on the limestone pavements of the Ingleborough area. He found that they were formed under a vegetation cover and suggested that organic acids, in addition to soil carbon dioxide, are important in solutional processes. He also made the interesting suggestion that some of the sediment found in caves is due to subsoil erosion, with soil particles being washed down widened joints, and indicated that this is an important process in limestone pavement formation. Further work on pavements followed by Parry (1960), Jones (1965) and Sweeting (1966). This latter paper recognises the possibility of enhanced solution due to industrial pollution. Also in this year Clayton (1966) described the various types of limestone feature found in the Malham area, including closed depressions, a much neglected topic.

The effect of geology both on surface and sub-surface features was also subject to much study around this time. Schwarzacher (1958) produced a lengthy paper describing limestone bedding whilst Doughty (1968) made a similar study of joint densities and their relation to lithology. Williams (1966) again using statistics attempted to apply morphometric analysis principles to the limestone landforms of this area, but his paper is not wholly convincing. In a different approach Norman and Waltham (1969) attempted to interpret geological structures and cave directions from aerial photographs. Although, with practice the former may be easily interpreted in limestone areas, the accuracy of the determination of cave direction is doubtful.

Sweeting and Sweeting (1969) stress the importance of lithology in the control of limestone erosion and thus the production of landforms. The general physiographic evolution of the Yorkshire Dales has recently been described by de Boer (in Rayner and Hemingway, 1974).

5. Summary

Throughout the development of limestone studies in Yorkshire it is possible to trace several stages and trends. The initial writings consist of descriptions of surface features with no attempt being made to explain their existence. These then developed into a more scientific approach to surface features with an attempt at explaining their formation and possibly some type of measurement of a feature being attempted, for example the discharge at the Ebbing and Flowing Well. A similar sequence of change can be seen in the study of underground features, although similar stages of analysis have always developed later in sub-surface work. However, as well as descriptions, interest in the science of caves was also fostered by water tracing, however unusual the methods, for example the woman's bonnet which was lost in Weathercote Cave and resurfaced in Hurtle Pot (Housman, 1808). Thus in quite early times there were numerous ideas on the origins of caves. With an increasingly "scientific" attitude being taken in the description of both surface and sub-surface features the next stage in development is marked by what might be defined as process-orientated studies, this becomes more and more evident as the degree of quantification increases. Parallel to these changes there has remained, especially in terms of caves, a purely descriptive type of writing, but even this has gradually become more accurate and factual.

Concurrent with this increasing quantification there is a second more recent trend to a much broader inter-disciplinary approach which is clearly shown by Richardson (1966), Cawood (1968) and Milner (1972). These descriptions of small areas or individual caves, in addition to discussing a large number of environmental factors affecting erosional development, also include such topics as historical and zoological description. This trend has been continued by the publication of 'Limestone and Caves of north-west England' (Waltham, 1974) and 'Geology and mineral resources of Yorkshire' (Rayner, 1974) both of which contain details of much recent research.

Acknowledgements

The author gratefully acknowledges the help of his wife in making a detailed check of the bibliography, and of the Hull University Inter-Library Loans office in obtaining copies of most of the sources of reference. The work was carried out whilst holding a Natural Environment Research Council studentship supervised by Dr. A.F. Pitty.

M.S. Received 4th December, 1974.

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Abbreviations

All are standard except for Y.R.C.J. — Yorkshire Ramblers Club Journal.

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Compiled by R.G. Picknett

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