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(5) THE CLOSED CIRCUIT OXYGEN APPARATUS¹

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AT the request initially of Mr. Shipton and later of the Himalayan Committee and Col. Sir John Hunt, closed circuit oxygen apparatus was prepared for the 1953 Mount Everest expedition. Serious studies on this problem could not be begun before November, 1952, and hence this work was unduly hurried. However, four training sets with forty canisters of soda lime were made and despatched on February 19, and an equal number of assault sets and canisters on March 19. This paper describes these sets, and then discusses the possible improvements.

Principle of Operation.

In these sets the oxygen was delivered into the circuit from a high pressure cylinder through a reducing valve and control valve, and inhaled in high concentration. The expired gases were then passed through a canister containing soda lime, which absorbed the CO₂ and allowed the oxygen and water vapour to enter a flexible breathing bag. On inspiration the wearer inhaled the oxygen from this breathing bag as well as a small quantity of fresh oxygen from the supply cylinder, but no outside air.

Parts of the Apparatus as Used. (See Figs. 1 and 2.)

The oxygen cylinders, pressure gauges, reducing valves and cellular helmets were identical with those supplied for the open circuit oxygen sets and described elsewhere. (R.C.London, *R.A.E. News*, 6, August 1953, 4.)

Carrier Frames. After field trials it was decided that rigid frames must be used for both open and closed circuit sets. A common frame was developed especially for those open circuit sets which used Royal Air Force cylinders and for the closed circuits. This was made of welded aluminium alloy tube, and was supported primarily on a webbing band across the pelvic brim, and secured by shoulder straps. The centre of gravity was high and close to the back. Bottle carriers supported either the light alloy cylinder or the R.A.F. cylinder horizontally across the frame.

Masks. Several patterns of masks were used during brief trials carried out by members of the party in Wales. Since no mask was

¹ The investigations on which this paper is based were made by the Electromedical Research Unit, Medical Research Council; the Stoke Mandeville Hospital; the R.A.E.; R.P.D., Westcott, Ministry of Supply.



FIG. 1.

CLOSED CIRCUIT OXYGEN APPARATUS SHOWING ONE OXYGEN CYLINDER AND TWO SODA-LIME CANISTERS.

[To face p. 242.]

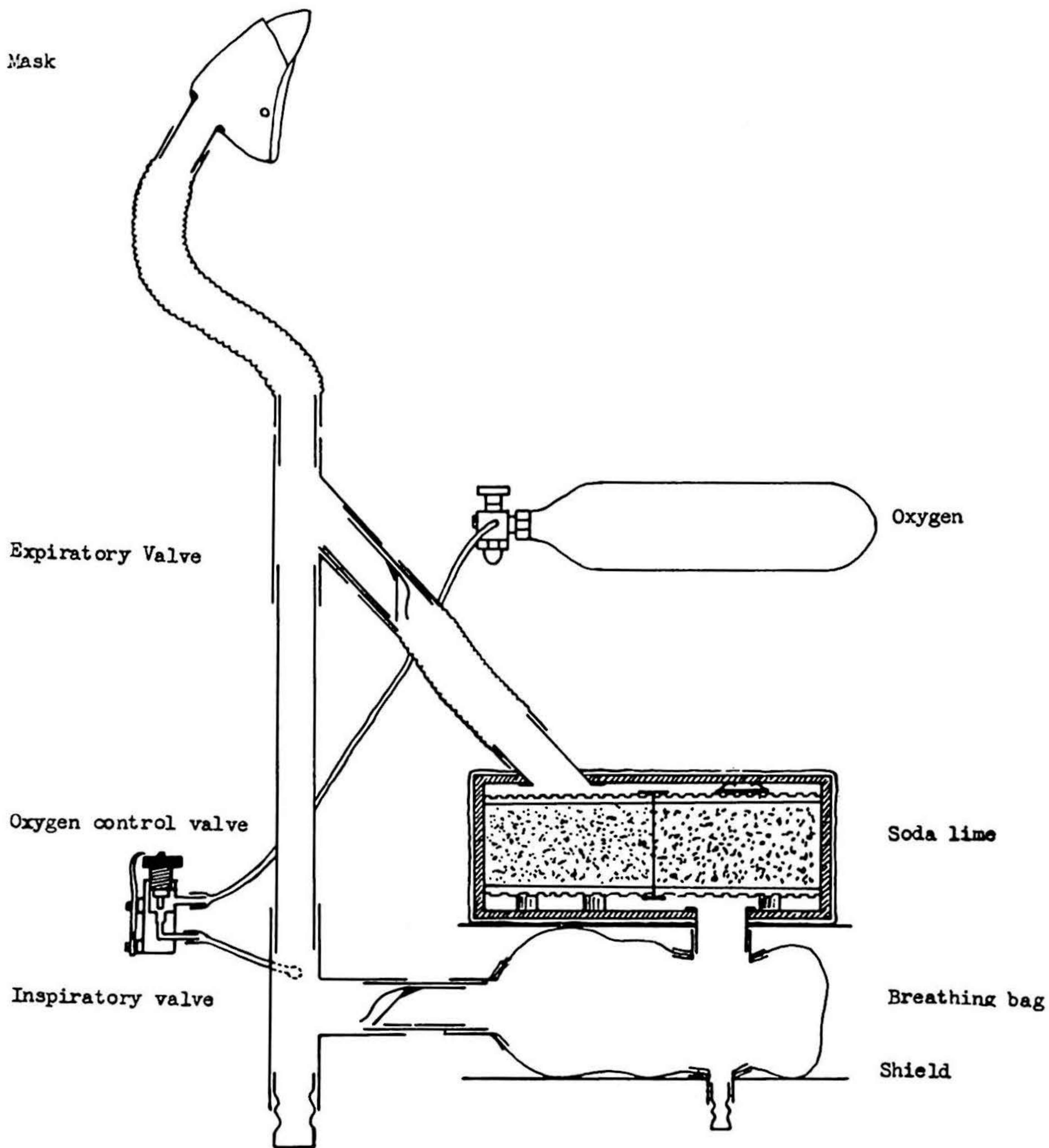


FIG. 2.

found satisfactory on all members of the party two types were supplied :

1. A pattern designed at the C.D.E.E., Porton, for use with portable resuscitators, and manufactured by the Avon India Rubber Co. of Melksham. This had one breathing tube (of $1\frac{1}{8}$ in. bore) and no valves. It was comfortable and fitted well except on faces with deep nose bridges. It was used in the assault, and is shown in Fig. 1.
2. A pattern supplied by Messrs. Veedip of Slough. This fitted well over any type of nose, but in prolonged wear was less comfortable, possibly owing to poor adaptation to the harness used. The same proved true of modifications of this pattern made in the laboratory. These masks incorporated a draining tube. No satisfactory method of draining the Porton mask was developed.

Two elastic straps joined to a cellular cotton helmet held the mask in place.

Razors. For a closed circuit a well fitting mask is essential. Since it is impractical to get an airtight fit over a beard, 'Viceroy' dry shaving razors were provided. Although found slow in use and rather heavy, these razors were used extensively at considerable altitudes, and by two men on the South Col at 25,800 ft.

Flexible Connector Tubes. After examination of a number of experimental corrugated connector tubes, a pattern manufactured by the Dunlop Rubber Co. of Manchester, was selected for use with the set. These sets were of rubber, covered with stockinette fabric and reinforced with a spiral spring of steel wire. The clear bore of the tubing was $1\frac{1}{8}$ in., giving a very low resistance to airflow, and the weight was approximately $4\frac{3}{4}$ oz. per ft. A short length at each end was made of plain rubber with the bore enlarged to $1\frac{1}{4}$ in.

A 9-in. length of this tubing was used to connect the expiratory valve to the canister, and a 15-in. or 18-in. length, according to the user's preference, to connect the mask to the Y-piece.

Rigid Connector Tubes. Short connector tubes of aluminium alloy were used where needed, and one alloy tube, 11 in. long, led up from the T-piece to the Y-piece of the set and was secured to the carrying frame (Fig. 1).

Insulating jackets of 'Aerogablex,' sewn between two layers of Jaconet were provided for this tube and for the directional valve housings.

The rubber Y-piece and T-piece were made by dipping wood moulds into a self-vulcanising black latex mixture supplied by Messrs. Veedip.

Directional Breathing Valves. In order to ensure the correct circulation of the gases in the circuit, two valves were fitted, of the 'Tissot' pattern, each with a sloping flap made of $\frac{1}{16}$ -in. sheet rubber, or alternatively of a double layer of thin polythene sheet stiffened by an insertion of aluminium foil. The valves tended to close, owing partly to the natural elasticity of the rubber and partly to the effect of gravity.

A light check spring of phosphor bronze prevented the flap opening too far. The flaps were attached to hard plastic tubing of bore $1\frac{1}{8}$ in.

It will be seen from Fig. 2 that on expiration of air from the lungs, the positive pressure produced in the upper flexible tube and in the long vertical tube opened the expiratory valve and closed the inspiratory valve; and on inspiration, the negative pressure induced in the same tubes, opened the inspiratory valve and closed the expiratory valve, thus causing the desired circulation.

Soda Lime Canister. The canister containing the CO_2 absorbent consisted of a rectangular box (11 in. \times $5\frac{1}{2}$ in. \times $4\frac{3}{4}$ in. internal), of tinfoil $.012$ in. thick, reinforced by tinfoil stiffeners. The cover was soldered in place after the assembly of the complete canister.

The bed of soda lime granules was supported on a horizontal diaphragm of steel wire gauze (11 in. \times $5\frac{1}{2}$ in.) which was soldered to the vertical walls of the canister. The bed was $3\frac{1}{8}$ in. in depth and was divided into two equal parts by a vertical plate soldered to the longitudinal walls of the canister. This division made possible the use of a smaller and simpler filling machine, and also strengthened the canister.

A diaphragm of steel wire gauze ($5\frac{1}{2}$ in. \times $5\frac{1}{2}$ in., 10 mesh per in., 22 S.W.G.) was fitted on top of each half of the bed of absorbent and held in place by a spring compressor.

A non-absorbent cotton dust filter (of weight 1.0 to 1.2 grains per sq. in.) was assembled between the soda lime and each wire diaphragm.

Metal spacing strips $\frac{3}{4}$ in. deep were placed between the bottom diaphragm and the canister cover.

The spigots were made of brass tubing with a bore of $1\frac{5}{16}$ in. and were kept closed by bark corks from the time of assembly until immediately before use. To prevent damage from changes in atmospheric pressure during transport, one cork was pierced by a brass tube plugged with a cigarette filter of cotton fibre, which allowed slow entry or exit of air as needed.

To conserve heat the canisters were provided with a cover of 'Aeroblex,' $\frac{1}{4}$ in. thick and an outer wrap of Jaconet. These covers were easily removed when loss of heat was desired.

Soda Lime. The soda lime used was supplied to Ministry of Supply Specification CS.2580, with 98% of the granules passing a sieve of 6 mesh per inch, but not passing one of 25 mesh. It was stated to absorb not less than 30% of its weight of CO_2 before passing 1% of CO_2 under test conditions.

Filling of Canisters. The efficiency of a soda lime canister depends greatly on the closeness and uniformity of the packing of the granules. If these are loose, channels of lessened air resistance form and as an undue proportion of air passes through these channels, the neighbouring granules become exhausted unduly soon, and the canister transmits CO_2 before the bulk of the granules are exhausted. To reduce the

danger of such 'channelling' a number of precautions were taken as follows:—

1. It was arranged that the gases should flow through the canister in a vertical direction so that if the granules loosened and a 'channel' formed along the top layer, the effect would not be disastrous.
2. A constant pressure totalling 60 lbs. was applied to the mass by two steel springs placed between the lid of the canister and the upper steel gauze.
3. The canister was filled by a special machine designed by one of us (E. H.), Brit. patent 2050/46 of 1946, and kindly loaned to us by C.D.E.E., Porton. This filling machine gave both denser and more uniform packing of the granules than did hand filling.

The overall density of the granules thus packed was approximately 0.87, each canister holding approximately 2,703 gm. of soda lime (5.96 lbs.) in 3,100 cc.

The Breathing Bags were made from rubberised fabric. They had a capacity of about 14 litres, and were fitted with a rubber inlet tube of $1\frac{1}{4}$ in. bore which could easily be slipped on or off the exit spigot of the canister. A similar exit tube led to the inspiratory valve. To protect the bag from rocks a curved aluminium alloy shield was fitted to the lower part of the carrier frame.

The Oxygen Control Valves were calibrated and arranged to deliver from $\frac{1}{2}$ to 5 litres per minute when fed from a line pressure of 50 lbs./sq. in. In practice the line pressure delivered by the high pressure reducing valves varied over a wide range, and hence the calibration proved only a rough guide to the rate of flow. A stop was fitted to prevent damage to the valve from being screwed down too forcibly.

Weight of Sets. The complete set, including carrier frame with one light alloy 800 litre oxygen cylinder, and one insulated canister, weighed a total of $27\frac{3}{4}$ lbs. (sufficient for 3,000 ft. of ascent at normal rates); with one cylinder and two insulated canisters— $36\frac{1}{2}$ lbs.; or with two cylinders and two canisters—48 lbs. (estimated as enough for 6 to 7 hours climbing with some surplus of oxygen. In practice the lower work rates used by acclimatised men on Mt. Everest led to considerably greater endurance in hours per canister.)

Tests Made Before Departure.

Cold Tests. Owing to the short time available, only brief and inadequate tests were practicable. Thanks to the kind co-operation of the Institute of Aviation Medicine at Farnborough, three cold chamber tests were done at temperatures of between -20° C. and -30° C. and in a strong 'wind' from a fan. One test showed the great importance of allowing condensed moisture to drain freely to the lowest part of the system. A later test showed that after 3 hours cooling at temperatures falling to -30° C. the set could be worn for 45 minutes without appreciable formation of ice on the valves (with an oxygen consumption

of 2 litres/min.). This test was done on a dry set, and in the light of experience on Mt. Everest it seems probable that if a set already wet with moisture condensed from several hours breathing were used, the introduction of a fresh canister at -25° C. would cause serious formation of ice on the valves.

Tests of Canister Endurance (Feb. 1953). T. D. B., using this set on a Welsh hill covered with rather long vegetation and soft snow 6 ins. deep rising to 3 ft. in drifts, ascended 1,500 ft. in 1 hr. 10 mins., and after descending without using oxygen, ascended a further 1,500 ft. in 1 hr. 8 mins. During the total ascent of 3,000 ft. in 2 hrs. 18 mins., a single soda lime canister was used. This showed no signs of exhaustion at the end of the period. The apparent consumption of oxygen (as judged by decrease in weight of cylinder) was 450 litres, i.e. $3\frac{1}{4}$ litres/min., but between 20 litres and 30 litres of this was used for flushing out the set when first put on.

A Laboratory Test of a canister filled on March 19, in which air containing approximately 2.32% CO_2 was passed through the soda lime at a steady rate of 100 litres/min. without recirculation, showed a CO_2 content in the air leaving the canister, which rose from a negligible value rather suddenly to 1.1% after 3 hours 18 mins. The canister contained 6.06 lbs. of soda lime, and thus absorbed approximately 460 litres CO_2 at 18° C. (= 1.87 lbs.) before the effluent content reached 1.1%. This gives a ratio of 3.25 lbs. soda lime per lb. of CO_2 absorbed, but to allow for experimental errors and other sources of uncertainty, we think that not less than 3.5 lbs. of soda lime per lb. of CO_2 should be provided when mountaineering, and 4 lbs. is perhaps safer. Experience on Mt. Everest suggests that under some conditions as little as 3 lbs. may suffice. Roxburgh, in his valuable paper on oxygen equipment for Mt. Everest (*Geog. J.*, 109, 1947, 207) assumed 15 lbs. of soda lime as needed for $2\frac{1}{4}$ lbs. of oxygen. This figure presumably includes the weight of the canister containing the absorbent. If we assume a total loaded canister weight of 1.372 lbs. per lb. of soda lime, as in the set here described, and a respiratory quotient of 0.9, Roxburgh's figure becomes 3.93 lbs. of loaded canister per lb. of CO_2 —a figure appreciably higher than that found in our laboratory tests.

Resistance to Breathing. Especial efforts were made to reduce this to a minimum in view of the high ventilation rates expected. Laboratory tests on the complete set (less mask and bent tube from mask) at a uniform flow rate of 200 litres/min. at 300 ft. above sea level and approximately 18° C., showed a resistance to expiration ranging from 2.0 to 2.5 cm. of water pressure with different canisters of soda lime, and a resistance to inspiration of 0.8 cm. water gauge. The expiratory resistance was mainly due to the soda lime, this portion ranging from 1.4 to 1.8 cm. for fully packed canisters. The valves showed a resistance of about 0.3 cm. each. Similar tests with the complete set less mask on a human being showed a resistance to expiration reaching 1.0 cm. on moderate breathing and a maximum of 2.2 cm. on very violent expiration. The inspiratory resistance was very much less.

Control of Oxygen Supply. Tests on Welsh hills showed that it was desirable to vary the oxygen flow rate from 3 litres/min. during vigorous efforts, to 0.5 litres/min. when resting. Manual control was found to be practicable, since the wearer noticed at once if the breathing bag emptied during inspiration, and noticed almost as readily if he was expiring against resistance owing to the bag being too full. He could therefore adjust the control valve satisfactorily, although this was a slight nuisance.

Dead Space. Practical trials showed that serious inconvenience was caused to the wearer if two tubes led from the mask to the gear on his back, from restricting the movement of his head, or obstructing the line of sight to his feet, or by causing difficulty in loading or off-loading the set on his back. Therefore a single flexible tube was used from mask to the Y-piece at the back. This involved a considerable 'dead space,' the volume between the wearer's face and the expiratory valve reaching about 700 cc. with the 15-in. flexible tube, or 755 cc. with the 18-in. tube. While this volume would be undesirable when sleeping, and would cause an appreciable increase in ventilation rate when resting at sea level, it should have very little effect at the high ventilation rates likely in 'acclimatised' persons, and might even be advantageous in aiding the restoration of plasma bicarbonate level after over-breathing in camp at over 24,000 ft. The reports from the Everest expedition showed that no inconvenience was noted from this cause.

Use as Open Circuit Set. On disconnecting the flexible tube just below the expiratory valve, and also the breathing bag from the inspiratory valve, this set could be used as an open circuit set, with the vertical alloy tube acting as an oxygen storage tube, as in the set described by Greene (*Lancet*, 1934, ii. 1122) as prepared for the 1933 expedition.

PRINCIPLES INVOLVED IN DESIGN

Had longer time been available, a number of improvements would have been introduced, making this set both more reliable and more convenient in use. The following note shows some of the problems involved :—

1. Reason for rejecting To-and-Fro Breathing.

The danger of ice formation on valves makes a valveless set appear most attractive. Of such sets, those in which the wearer breathes to and fro through the soda lime canister are the simplest. Sets of this type are known to be useful where small canisters are concerned. But if large canisters are needed, the 'dead space,' or volume of air which is rebreathed without passing through effective soda lime, becomes prohibitive. Thus 2 kilogrammes (4.4 lbs.) of soda lime packed to an overall density of 0.9 include an air space between the granules of about 1,100 cc. Since the soda lime becomes exhausted in successive layers from the surface at which the air enters, the effective dead space becomes larger as the canister is used up, and towards the end of its

life nearly the whole of the intergranular space acts as 'dead space.' To this must be added the considerable dead space between the entry tube of the canister and the soda lime filter, as well as that in the mask and connecting tube. Practical trials with a large canister in Wales showed serious hyper-ventilation, apparently from this cause, and we had to abandon this system since the alternative was to ask climbers to use small canisters and change them perhaps every hour.

2. *Injector Systems.*

The breathing valves can also be dispensed with if the oxygen supply is passed through an injector arranged to blow the gases in one direction round the circuit. After a few experiments we abandoned this method owing to the difficulty of coping both with the high ventilation rates expected in active climbing and the big drop in oxygen supply needed when resting. Further study might overcome these difficulties.

3. *Control of Oxygen Supply.*

Ideally this should be obtained by an automatic 'demand' valve, as used by Messrs. Siebe, Gorman in the 1938 Everest closed circuit set described by Peter Lloyd (*Nature*, 143, 1939, 961). Such a valve could be made to respond either to the pressure of a collapsed breathing bag or to a slight suction pressure produced on inspiration. Owing to the short time available for design and test, we felt unable to use either of these types, and therefore relied on manual control.

In future sets, automatic control would seem preferable, provided that it is reliable under all conditions, and does not risk mask leakage from negative pressure, or oxygen waste and fatigue from using a mean positive pressure.

4. *Protection from Freezing.*

It seems clear that suitable soda lime will function adequately at -20° C. but less completely at -30° C., and at -40° C. might be expected to fail. In reasonable weather spare canisters carried on the back with suitable insulation are not likely to fall below -30° C., but the danger remains that on inserting a new canister into a breathing set with moist valves, ice may form on the valves and prevent them from moving (as happened sometimes on Mt. Everest). The following method of avoiding this appears simple and likely to be reliable. When preparing to change canisters the new one could be connected between the expiratory valve and the old canister and the two used in series for the next ten or fifteen minutes. After that the old canister would be discarded. This would give the climber a little extra trouble, but could be made easy for him to do.

An alternative method would be to fit a chlorate 'candle' to the lower part of each canister so as both to warm the air chilled by the cold soda lime, and to provide some extra oxygen to counteract the weight of the 'candle.' These candles have been developed for use in other types of breathing equipment.

Another possible method would be when inserting a new canister

to leave the lower end disconnected for 10 or 15 minutes, and meanwhile to use the set as an open circuit one.

5. *Dispersal of Heat.*

While at very high altitudes the warmth evolved by the soda lime must usually prove a valuable asset, there are situations as in the Western Cwm of Everest, where it is objectionable. In a fresh design some of this difficulty could be avoided, but at altitudes where heat is likely to be troublesome, the possible advantages of closed circuit over open circuit equipment are much reduced, and it may be less trouble to use the open circuit.

6. *Choice of Absorbent.*

For 1953, soda lime was chosen because other absorbents of CO_2 were not available in the necessary quantity in this country. For future expeditions it is obvious that full consideration should be given to the great saving in weight obtainable by using, as sources of oxygen and absorbents of carbon dioxide, the peroxides of alkalis or alkaline earths, with or without hydrogen peroxide. If the practical difficulties of controlling reaction rates under mountaineering conditions could be overcome, chemicals of this type would obviate the need for oxygen cylinders altogether.

7. *Mask Harness and Mask Leakage.*

It is important to note that closed circuit equipment at altitudes below 29,000 ft. is potentially more dangerous than well designed open circuit sets. In the latter type, mask leakage cannot at the very worst reduce the oxygen content of inspired air to less than that in the external atmosphere. In a closed circuit set any considerable mask leakage occurring on inspiration can reduce the oxygen seriously, although it is not likely to fall below that of the outside air unless the oxygen supply from the cylinder ceases. But if this does cease, then serious mask leakage would cause the accumulation of so much nitrogen in the set that unconsciousness might supervene from lack of oxygen. For this reason as well as for ease of fitting, we think that closed circuit masks for mountaineers should be held by elastic straps applied to two studs only, and not four. With two-stud harness a climber who suddenly feels something wrong can push his mask off the mouth with a single brusque movement, and so breathe free air.

8. *Savings in Weight.*

The use of modern plastics should allow of appreciable saving in weight in future sets, provided that brittleness at -30°C . can be avoided. For certain climbs a smaller canister holding only 4 lbs. might prove advantageous. This would, however, involve a higher resistance, or else a shallower bed of absorbent with increased risk of 'channelling.'

9. If given time for proper trials, valves could be moulded in rubber that could be freed from ice by external kneading with gloved fingers.

The Relative Advantages of Closed Circuit and Open Circuit Equipment.

Final judgment on this question should await comparative trials in the Himalayas of equipment designed and made without undue haste. It is, however, possible to assess some features as follows.

The chief advantages of the open circuit are :—

1. It probably has greater simplicity.
2. Less training is needed for its efficient use.
3. In hot situations it is cooler for the wearer.
4. If sufficient oxygen is available it can be used while sleeping, although it may be wiser to provide special sets for this purpose, as was done in 1953.

The chief advantages of the closed circuit are :—

1. A much higher concentration of oxygen is obtained by the user. Hence a greater climbing rate is to be expected, the gain becoming marked (for a given weight carried) at heights above 23,000 or 24,000 ft. The extent of the gain is uncertain, since 'acclimatisation' reduces a man's capacity to use oxygen, and it is uncertain how rapidly he recovers this capacity when given a supply at sea level concentration. In spite of this quantitative uncertainty, the gain appears likely to be of great importance, by allowing the use of a lower top camp and fewer high camps, thus permitting the attainment of a given objective by a much smaller expedition (Matthews, *Geog. J.*, 90, 1937, 143).
2. Great conservation of heat—of especial value in cold weather and at great altitudes (Matthews, *J. physiol.*, 77, 1933, 28P).
3. Conservation of moisture, preventing excessive drying and chilling of the nose, throat and trachea.
4. Major saving in oxygen at all heights where oxygen is needed.

The experience of the Swiss expedition in 1952 (Dittert, *Alpinisme*, 1952, p. 85) showed clearly that it is undesirable to spend a night at 25,800 ft. (as on the S. Col of Mt. Everest) without the use of oxygen while sleeping. It seems reasonable to conclude that expeditions to very high mountains should take open circuit equipment for use while sleeping above 23,000 ft. and closed circuit equipment for use while climbing.

We wish to thank members of the staff of C.D.E.E., Porton, of the Institute of Aviation Medicine, R.A.E., Farnborough, and of R.P.D., Westcott, for much helpful advice and co-operation; and members of the Electro-medical Research Unit—Dr. F. D. Stott, Miss A. Cullis, Miss S. Wolfenden, and the Technical staff—Mr. E. Pitte, Mr. F. E. Bew and Mr. R. Strads, for working long hours at high pressure up till March 19.

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