Paper ho 1.

First Report of the

vive Rescue Apparatus Research Committee.
DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH.

ADVISORY COUNCIL.

FIRST REPORT
OF THE
MINE RESCUE APPARATUS RESEARCH COMMITTEE.

LONDON:
Published for the Department of Scientific and Industrial Research by His Majesty's Stationery Office and to be purchased at the addresses named inside the cover.
1918.
(Reprinted 1920.)
Price 2s. Net.
GOVERNMENT PUBLICATIONS
(with the under-mentioned exceptions)

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The Journal of the Board of Agriculture and Fisheries is published monthly by the Board, and is obtainable from 3, St. James's Square, London, S.W.1. Price (since Jan. 1, 1920) 6d., post free.

The following is a list of some Parliamentary and Official Publications (All prices are net, and those in parentheses include postage):

SPONTANEOUS COMBUSTION OF COAL IN MINES.

FIRST REPORT OF THE DEPARTMENTAL COMMITTEE:—Comparative Liability to Spontaneous Combustion in Mines as between different Districts in the United Kingdom; Loss of Life occasioned by Fires due to Spontaneous Combustion in Mines in the United Kingdom; "Gob" Fires regarded as Dangerous Occurrences; The Stage at which Abnormal Heating should be reported to the Inspector of Mines; The Question of the Withdrawal of Workmen from a Mine or part of a Mine on the Outbreak of Fire, or during the Operations of dealing with the Fire; Memoranda from various Members of the Committee.

[Cd. 7218] of Session 1914. Price 1½d. (2½d.)

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH.

MINE RESCUE APPARATUS RESEARCH. SECOND REPORT OF THE COMMITTEE:—Introduction; Physiological Considerations and Experiments; Deaths due to Rescue Apparatus; Approval of Mine Rescue Apparatus; Miscellaneous; Appendices: The Briggs Compressed Oxygen Mine Rescue Apparatus; Fitness testing with the Ergometer. With Plates and Diagrams. (1920.) Price 2s. (2s. 2d.)

PREFATORY NOTE.

The Advisory Council for Scientific and Industrial Research appointed in May, 1917, on the suggestion of the Home Office, a Committee to investigate the types of breathing apparatus used in coal mines. The Committee consists of:—

Mr. William Walker, C.B.E., Acting Chief Inspector of Mines (Chairman).
Mr. Henry Briggs, D.Sc.
Mr. John Haldane, M.D., LL.D., F.R.S.

Dr. Briggs, Head of the Department of Mining in the Heriot-Watt College, Edinburgh, was appointed Director of the experimental work involved in the Research, and the Governors of the Heriot Trust kindly consented to allow facilities for this experimental work to be provided at the Heriot-Watt College, where two assistants appointed by the Advisory Council have been at work under the supervision of Dr. Briggs during the last year.

This Report of the first year’s investigations is published with the concurrence of the Home Office and the Air Ministry, the information contained in the Report being, in their opinion, likely to prove valuable to all concerned with the use of such apparatus. The Chemical Warfare Department of the Ministry of Munitions have also been consulted and have approved of the publication of the Report.

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH,
15, Great George Street, Westminster, S.W.1.
1918.
LIST OF ILLUSTRATIONS.

Frontispiece.—Map showing the positions of central mine rescue stations and sub-stations in the United Kingdom. Sub-stations are indicated by italicised printing. A circle of 10 miles radius is described about each station.

Fig. 1. Henry A. Fleuss and group of miners, equipped with earliest Fleuss apparatus and oxygen lamps. Seabam Colliery, 1881.

2. Proto apparatus, front view.
3. " " " side view.
4. " " " reducing valve and connections.
5. " " " flow diagram.
6. Draeger apparatus, 1907, front view.
7. " " " back view.
8. " " 1911, front view.
9. " " " back view.
10. " " 1913, flow diagram.
12. " " " back view.
13. " " " flow diagram.
15. " " " back view.
16. " " oxygen cylinders and connections.
17. Aerophor, front view.
18. " " " back view.
19. " " charging with liquid air.
20. " " use of auxiliary connection.
22. Tissot apparatus, back view.
23. " " " mouthpiece attachment.
24. " " " cylinder connections.
25. " " " flow diagram.
27. " " " back view (cover removed).
28. " " " flow diagram.
29. Sunk spindle valve.
30. Key for sunk spindle valve.
31. Appliance for testing pressure gauges.
32. Haldane's litre-meter.
33. Briggs' litre-meter.
34. Draeger's bag.
35. Combined testing set.
36. Sectional ventilation plan prepared for rescue brigade.
37. Graham's oxygen analysis apparatus.
38. Briggs' oxygen analysis apparatus.
To the Advisory Council to the Committee of the Privy Council for Scientific and Industrial Research.

Gentlemen,

Owing to the unsatisfactory and sometimes fatal results obtained with some of the types of self-contained breathing apparatus at present in use, we were appointed by you, at the invitation of the Secretary of State for Home Affairs, to form a Research Committee under the following terms of reference:

"To inquire into the types of breathing apparatus used in coal mines, and by experiment to determine the advantages, limitations and defects of the several types of apparatus, what improvements in them are possible, whether it is advisable that the types used in mines should be standardised, and to collect evidence bearing on these points."

In this, our First Report, which we submit with the recommendation that it be published, we draw attention to certain serious defects in existing mine rescue apparatus, and in the training of men with those appliances, in order that the requisite steps may be taken without delay to remedy them. The Report serves a further purpose in indicating the lines along which improvement in apparatus is desired, in fixing standards of achievement, and, generally, in preparing the ground for further progress in experimental investigations.

We have so far directed our attention solely to the so-called two-hour types of breathing apparatus, leaving other forms for future consideration.

It is our intention to make further reports when the necessary work is completed.

For the purposes of making inquiry and inspecting the apparatus and stations, we have visited the following Rescue Stations:

<table>
<thead>
<tr>
<th>Names of Stations Visited</th>
<th>Situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aberaman</td>
<td>South Wales.</td>
</tr>
<tr>
<td>Abercynon</td>
<td>South Wales.</td>
</tr>
<tr>
<td>Altofts</td>
<td>Normanton, Yorkshire.</td>
</tr>
<tr>
<td>Barnsley</td>
<td>Yorkshire.</td>
</tr>
<tr>
<td>Brierley</td>
<td>Yorkshire.</td>
</tr>
<tr>
<td>Brigham</td>
<td>Cumberland.</td>
</tr>
<tr>
<td>Brynmenyn</td>
<td>South Wales.</td>
</tr>
<tr>
<td>Coatbridge</td>
<td>Lanarkshire.</td>
</tr>
<tr>
<td>Cowdenbeath</td>
<td>Fifeshire.</td>
</tr>
<tr>
<td>Crumlin</td>
<td>Monmouthshire.</td>
</tr>
<tr>
<td>Elswick</td>
<td>Newcastle-on-Tyne.</td>
</tr>
<tr>
<td>Heriot-Watt College</td>
<td>Edinburgh.</td>
</tr>
<tr>
<td>Howe Bridge</td>
<td>Lancashire.</td>
</tr>
<tr>
<td>Ilkeston</td>
<td>Derbyshire.</td>
</tr>
<tr>
<td>Kilmarnock</td>
<td>Ayrshire.</td>
</tr>
<tr>
<td>Llynfi Valley</td>
<td>Maesteg, South Wales.</td>
</tr>
<tr>
<td>Rhondda</td>
<td>Porth, South Wales.</td>
</tr>
<tr>
<td>Rhymney Valley</td>
<td>New Tredegar, South Wales.</td>
</tr>
<tr>
<td>Rotherham</td>
<td>Yorkshire.</td>
</tr>
<tr>
<td>Stoke-on-Trent</td>
<td>Staffordshire</td>
</tr>
<tr>
<td>Swansea</td>
<td>South Wales.</td>
</tr>
<tr>
<td>Tankersley</td>
<td>Yorkshire.</td>
</tr>
<tr>
<td>Wakefield</td>
<td>Yorkshire.</td>
</tr>
<tr>
<td>Wath-on-Dearne</td>
<td>Yorkshire.</td>
</tr>
</tbody>
</table>
We should like to place on record our appreciation of the great courtesy extended to us and the valuable information put at our disposal by the Committees of Management and Instructors of these Stations. The Rescue Stations we visited, almost without exception, proved to be well situated and excellently planned and furnished. We were impressed with their general efficiency, with the zeal and competence of the Instructors, and with the great trouble taken by the Committees of Management in superintending and organising the work.

We desire to express indebtedness to the Governing Body of the Heriot-Watt College for kindly affording full facilities for the experimental side of the research.

In July, 1917, you appointed Miss Elizabeth Gilchrist, M.A., B.Sc., and Mr. David Penman, B.Sc. (London and Edinburgh), respectively as chemical and general assistant to Dr. Briggs. We take the opportunity of thanking the Governors of the Dundee University College and the Committee of the Cowdenbeath Mining School for so readily granting them leave of absence to take up their duties in Edinburgh.

Research on rescue apparatus had been commenced at the Heriot-Watt College in September, 1916, the work being privately financed by Sir William Garforth. The experimental inquiry then started has been absorbed into the larger scheme of the Research Department, but, in providing a reconnaissance of the subject, it has proved most useful, and we wish to express our personal obligation to Sir William for so generously bearing the cost of that preliminary survey.

Mr. A. Richardson, M.Inst.M.M., of your Department was appointed Secretary; and at the first meeting of the Committee Mr. Walker was elected Chairman and Dr. Briggs Director of Experimental Work.

While we make somewhat drastic recommendations in regard to the present-day apparatus it must not be inferred that we do not appreciate the excellent qualities of some of the types and the valuable work done by those who have laboured to bring them to their present stage. The defects in our opinion are mainly in matters of detail, and if improved in the way we suggest in this report the apparatus should be capable of doing rescue and recovery work under the most trying circumstances.

Much credit is due for the work which has been carried out by Colonel W. C. Blackett and Mr. F. P. Mills in connection with the Liquid Air apparatus used at the rescue stations in Northumberland and Durham. Their efforts have resulted in many improvements being made in the apparatus, and it can now be used for hard work, whereas in the form in which it was originally supplied it was of no practical use for underground purposes. We hope that one result of our labours will be still further to increase the efficiency of this type. We highly appreciate, and readily accept Colonel Blackett's offer of co-operation in further experiment in this connection.

As regards oxygen apparatus, the pioneer inventor is Mr. Henry A. Fleuss, whose original apparatus (of which we reproduce a very interesting photograph) was the subject of inquiry by the Royal Commission of Mines so long ago as 1880-1886. The main features of his design are still represented in the Proto and other apparatus of to-day. Excellent work has also been done by Sir W. E. Garforth; Professor Sir John Cadman; Mr. R. H. Davis, of Messrs. Siebe, Gorman & Co.; Mr. George Blake Walker, of Tankersley, and a number of the superintendents at the rescue stations, and for this work they deserve the thanks and appreciation of all connected with mining.

We are under obligation to the French and American Governments for the Tiisot and Gibbs apparatus lent to us for inspection and test; and we are also indebted to the superintendents of the New Tredegar, Porth, and Rotherham stations for their assistance in preparing photographs.

The most important reports, in English, on mine rescue apparatus are the following. The abbreviated and italicised titles in brackets are those used in the text for purposes of reference:

First Report of the Royal Commission on Mines, 1907. (Cd. 3548.)
Report to the Doncaster Coal Owners' Committee (Gob Fire Research) on Self-contained Rescue Apparatus for use in Irrespirable Atmospheres, by J. S. Haldane, Part I, 1914 (First Doncaster Report); Part II, 1915 (Second...


The following regulations are in force in respect of the supply and maintenance of appliances for use in mine rescue work and of the formation and training of rescue brigades:—

Coal Mines Act, 1911, Section 55 (Rescue Work and Ambulance).

General Regulations, Part IV, Nos. 138 to 146 inclusive (Regulations and Orders under the Coal Mines Act, 1913 edition, p. 26).

Amended General Regulations of 19th May, 1914.

Schemes of Training and Practice.

The last three sets of rules are to be found in the Home Office Pamphlet of February, 1915 (Mines and Quarries Form, No. 72), price 4d.

PART I.

EXISTING SELF-CONTAINED RESCUE APPARATUS.

List of Existing Apparatus.—Table I. furnishes a list of existing rescue apparatus and certain particulars relating to them. These apparatus are briefly described, seriatim, in the present Part of the Report.

Table I.

<table>
<thead>
<tr>
<th>Name of Apparatus</th>
<th>Year of Introduction of Original Model</th>
<th>Nationality</th>
<th>Weight when Charged</th>
<th>Nature of Oxygen Supply</th>
<th>Circulatory Agent</th>
<th>Number in use at British Rescue Stations and Mines: 1916 figs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proto or Fleuss</td>
<td>1879</td>
<td>British</td>
<td>36 lbs.</td>
<td>Constant feed or hand-adjusted feed.</td>
<td>Lungs</td>
<td>913</td>
</tr>
<tr>
<td>Draeger</td>
<td>...</td>
<td>German</td>
<td></td>
<td></td>
<td>Constant feed</td>
<td>220</td>
</tr>
<tr>
<td>Meeco, Westfallia, or Securitas</td>
<td>1906</td>
<td>German*</td>
<td>35 lbs.</td>
<td>Constant feed</td>
<td>Injector</td>
<td>455</td>
</tr>
<tr>
<td>Weg</td>
<td>...</td>
<td>British</td>
<td>40 lbs.</td>
<td>Automatically controlled.</td>
<td>Lungs</td>
<td>132</td>
</tr>
<tr>
<td>Aerolith</td>
<td>...</td>
<td>Austrian</td>
<td>22 lbs.</td>
<td>Liquid Air...</td>
<td>Evaporation of Liquid Air...</td>
<td>96</td>
</tr>
<tr>
<td>Aerophor</td>
<td>...</td>
<td>British</td>
<td>50 lbs.</td>
<td>Liquid Air...</td>
<td>Evaporation of Liquid Air...</td>
<td>Nil</td>
</tr>
<tr>
<td>Tissot</td>
<td>1907</td>
<td>French</td>
<td>32 1/2 lbs.</td>
<td>Hand-adjusted feed.</td>
<td>Lungs</td>
<td>Nil</td>
</tr>
<tr>
<td>Gibbs</td>
<td>1917</td>
<td>American</td>
<td>30 lbs.</td>
<td>Automatically controlled.</td>
<td>Lungs</td>
<td>Nil</td>
</tr>
<tr>
<td>Pneumatogen</td>
<td>1904</td>
<td>Austrian</td>
<td>14 1/2 lbs.</td>
<td>By chemical action on oxy lith.</td>
<td>Lungs</td>
<td>Nil</td>
</tr>
</tbody>
</table>

Proto Apparatus.—The present day Proto apparatus has developed from the original design of Fleuss, whose first patents are dated 1879. We are indebted to Mr. Fleuss for the photograph reproduced in Fig. 1. This photograph has great historical interest, for not only does it show the earliest self-contained breathing apparatus which could claim anything approaching practical utility, but it records the first application of such apparatus in mining. It was taken at the time of the underground fire which followed upon the explosion at Seaham Colliery, 1880-81.
The modern Proto (Messrs. Siebe, Gorman, London) is illustrated by photographs (Figs. 2 and 3) giving front and side views of a man wearing the apparatus; by a photograph (Fig. 4) of the reducing valve and connections thereto, and by the flow diagram (Fig. 5).

**Fig. 5.—Proto Apparatus, Flow Diagram.**

The apparatus has the merit of simplicity. The circulation is dependent on the lungs of the wearer, breathing being entirely through the mouth. The cylinders, B, together hold 280 litres of oxygen under a pressure of 120 atmospheres. The reducing valve C, when correctly adjusted, allows a constant flow of oxygen of 2 litres (122 c. in.) a minute to pass into the breathing circuit. The makers also supply reducing valves which can be set by the wearer to give discharges ranging between 0·6 and 3 litres per minute. The oxygen passes through a flexible tube F, running over the wearer's left shoulder, and enters the bag at N, where it joins the air being drawn into the lungs. Light mica valves are fitted in the tubes at M and L to control the direction of flow of the air. The breathing bag, which is of rubber, is divided into two compartments by a partition reaching nearly to the bottom, and in the bottom of the bag is placed a charge of caustic soda weighing 3 to 5 lbs. Either stick soda is employed or coke nuts coated with caustic. The air, in travelling from one compartment of the bag to the other, has thus to find its way through the soda, and, in doing so, the CO₂ is absorbed. By shaking the bag from time to time new surfaces of the absorbent are exposed to the air, and the absorption of CO₂ is facilitated. A saliva trap Z is fitted under the exhaling tube. The pressure gauge, which is carried in a pocket in front of the bag, is connected to the oxygen supply by means of a highly flexible metal tube W. The wearer can thus read his own gauge. A relief valve, operated by the wearer, is placed on the bag at S. Fig. 3 shows how, by means of a strong steel neck, the main valve wheel H is brought to the front within reach of the wearer. The by-pass tube J (Fig. 4) short-circuits the reducing valve C. Oxygen can be discharged through the by-pass by opening the cock I. V is the pressure gauge valve. It is only opened when the gauge is to be read.
Fig. 1.—Henry A. Fleuss and group of miners, equipped with earliest Fleuss apparatus and oxygen lamps. Seaham Colliery, 1881.

Fig. 2.—Proto apparatus, front view.
FIG. 3—PROTO APPARATUS, SIDE VIEW.

FIG. 4—PROTO APPARATUS, REDUCING VALVE AND CONNECTIONS.
Plate III.

Fig. 6.—Draeger Apparatus, 1907, Front View.

Fig. 7.—Draeger Apparatus, 1907, Back View.
The Draeger Apparatus.—The Draeger apparatus has been widely adopted in this country and America, and especially in Germany, where it is used for Army purposes as well as for mines. The oxygen, which is supplied at a constant rate of 2 litres per minute, enters the breathing circuit through an injector nozzle I (Fig. 10), thereby inducing an air circulation independent of the lungs. The circulation is intended to be circa 60 litres per minute. The flow diagram is that of the last Draeger to be introduced into this country. In that model the purifier P and cooler K are on the discharge side of the injector, and therefore tend to be under positive pressure. The two types of Draeger most commonly seen are the 1907 model (Figs. 6 and 7) and the 1910 form (Figs. 8 and 9), and in both these the purifier and cooler are on the suction side of the injector, an arrangement which has the objection of leading to inward leakage should there be a faulty joint or puncture in those parts. Mica valves in the metal portion of the mouthpiece attachment direct the air entering and leaving the lungs. The two compartments of the bag B are connected by a narrow passage p, whose purpose and drawbacks will be subsequently discussed (see pp. 23, 24). The pressure gauge G is usually at the back, out of sight of the wearer, the leader of the brigade being intended to take all gauge readings. In the most recent forms, however, a front reading gauge is provided; it is connected to the oxygen supply pipe by a flexible tube, and is kept in a leather pocket on the left shoulder.

In the 1907 type, the oxygen cylinders are double and are both fitted with valves. The danger of reserving one cylinder until the other is exhausted—as was originally the intention—is generally known, and now both valves are opened at the commencement of the period of use. The 1910 type has a single, vertical oxygen cylinder (Fig. 9). There is no by-pass. The purifier, shown at P in Fig. 7, consists of two cylindrical cartridges placed in parallel, while that of Fig. 9 is a single and larger cartridge of oval section. The Draeger cartridges imported from Germany contained granules of both caustic potash and caustic soda. The inferior variety, filled in this country, contains the latter absorbent only. The internal arrangement of the cartridges is excellent.

By simplifying the mode of connection of the purifier, and by introducing smoke excluding valves (A_1 and A_2 (Fig. 10)) which automatically close when the cartridge is withdrawn, it is now possible to change an old cartridge for a new one while in a foul atmosphere. A spanner is secured to the back of the more recent apparatus to enable the oxygen cylinder also to be changed in bad air.

The Meco Apparatus.—The Meco apparatus (Mining Engineering Co., Ltd., Sheffield) has developed from the Shamrock, which was described in the First

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**Fig. 10.—DRAEGER APPARATUS, 1913, FLOW DIAGRAM.**

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Report of the Royal Commission on Mines, 1907. It is identical with that known as the Westfalia in Germany and America, and the Securitas in Belgium. It is illustrated in Figs. 11 and 12, and by the flow-diagram, Fig. 13. C are the cylinders, weighing about 14 lb., and holding 265 litres of "free" oxygen compressed to 120 atmospheres. The oxygen passes through the reducing valve R; then through an injector nozzle at I (Fig. 13) and into the breathing circuit. The reducing valve is adjusted so that a constant flow of 2 litres per minute is obtained. The rate of oxygen discharged is not under the control of the wearer. There is no by-pass. In most Meco apparatus the pressure gauge is fixed at the back, but in the apparatus illustrated a front reading gauge G is provided. It is connected to the cylinders by a flexible metal tube, and held in the pocket a (Fig. 11). The "automat" is the same as that of the Draeger. P is the purifier containing granular caustic soda held in gauze trays arranged baffle-plate fashion. T is a metal cooling tube. The breathing bag B is in two parts respectively connected to the inspiratory and expiratory tubes. The latter tube also serves as a saliva conduit, the saliva trap S being placed under the bag. The relief valve, which is automatic in action, is usually at r (Fig. 13). More recently it has been fitted to the tube leading to the purifier. There are no valves in the breathing circuit, the injector being entirely responsible for maintaining the circulation.

The W.g Apparatus.—This apparatus derives its name from the initials of its inventor Sir William E. Garforth. It embodies some interesting novelties of design. As the adjoining figures show, the apparatus leaves the front of the wearer as clear as possible. There are two curved oxygen cylinders, carried low down, one on each side. They are connected together by the narrow bore tube t (Fig. 16). The two valve wheels, c, c, which are within easy reach, are opened together. The gauge G is at the front. The cover which protects the face of the gauge has a mirror on its inner surface, enabling the wearer to take the readings by reflection. The cylinders hold 300 litres compressed to 150 atmospheres. The breathing bag B and the purifier P (in leather case) are at the back. The face attachment is the half mask M, to which are connected the inhalation and exhalation tubes. These tubes (which are provided with valves) pass over the head, being supported by a leather skull-cap. The exhaled air flows to the purifier; thence to the bag and back again to the inspiratory tube, where it is met by the oxygen stream entering by the tube T. The most distinctive feature of the apparatus is the "lung-governed" valve V. This is a delicate reducing valve with large diaphragm adjusted to open during inhalation and to close on exhalation. The object of the valve is to provide automatically for the varying oxygen consumption of the lungs. The lung-governed valve has undergone several improvements since it was originally introduced in 1906. In the latest design there are two reducing valves in series. The first brings down the pressure of supply to 10 lbs. per sq. inch. The other admits oxygen to the breathing circuit as soon as the pressure in that circuit sinks to a predetermined figure (e.g., 3-inch positive pressure), and closes when the pressure is restored to, say, 2 inches of water column. In Fig. 6, b is the by-pass tap and a a tap, normally open, by which the passage to the reducing valve can be closed if the latter should fail. On such an occasion the wearer would depend entirely on the by-pass until he could reach fresh air.

In the latest model an increase in the diameter of the tubes and valves of the circuit has appreciably reduced the resistance to breathing. A mouthpiece apparatus has also been made.

Liquid Air Apparatus: (a) The Aerolith Apparatus.—In the "Aerolith," Suess' original liquid air apparatus—of which drawings and a description are to be found in the First Report of the Royal Commission on Mines, 1907—no attempt was made at regeneration. The air expelled from the lungs partly made its escape and partly was breathed over again, being augmented by fresh air evaporated from the liquid supply held in a "pack." Except for the first part of the period of use, when a very vigorous evaporation took place, this arrangement naturally proved unworkable, especially if the wearer exerted himself. The discharge went along a tube passing through the liquid air receptacle. The ice forming in that tube led to excessive resistance in the earlier models of the Aerolith.
Fig. 11.—Meco Apparatus, Front View.

Fig. 12.—Meco Apparatus, Back View.
PLATE VI.

Fig. 13.—Meco Apparatus, Flow Diagram.

Fig. 16.—Weg Apparatus, Oxygen Cylinders and Connections.
FIG. 14. - Weg Apparatus, Side View.

FIG. 15. - Weg Apparatus, Back View.
Fig. 17.—Aerophone, Front View.

Fig. 18.—Aerophone, Back View.
(b) The Aerophor Apparatus.—The "Aerophor" apparatus (Blackett's patents 1910 and 1911) is illustrated by Figs. 17 to 21. It will be observed that the receptacle \( A \), holding the charge of 8 or 10 lbs. of liquid air (which, in practice, always contains over 60 per cent. of oxygen), is carried, together with the purifier \( U \), on the wearer's back, while the breathing bag \( B \) is at the front. To prevent the wearer being affected by the extreme cold of the pack, the canvas jacket which supports the apparatus is padded at the back with felt, and an air-space is left between the padding and the pack. At the Northumberland and Durham stations the half-mask is employed, while at the Rotherham station—where the accompanying photographs were taken—the mouthpiece is used. The absorbent material within the metal receptacle is asbestos wool. After considerable experiment at Newcastle, a thoroughly satisfactory distributing arrangement, diagrammatically shown in Fig. 21, has been devised, whereby the liquid air, poured in through the central opening at the top of the pack, is spread rapidly and uniformly in the wool. It enables the pack to be charged in one minute. The manner of charging is illustrated in Fig. 19. Liquid air is being poured from a large Dewar storage bottle into the pack. The spring balance from which the pack is hung, measures the charge. The receptacle is insulated by kieselguhr, felt, and a final cover of leather. The insulation permits the penetration of sufficient heat to volatilize the liquid air at the required rate.

During the earlier part of the period of use the volume of volatilized air passing out of the tube \( E \) is more than enough to supply the wearer's requirements. The current at this stage divides at \( J \), one part going to the lungs and the other passing to waste through \( U \) and the automatic relief valve \( R \). The exhaled air also discharges through \( R \). Later in the period, when the evaporation is less rapid, the lungs can only get the volume they call for by rebreathing a portion of the exhaled air. The flow in the purifier now reverses; the apparatus becomes a regenerator, and the purifier removes the CO\(_2\) and moisture from that part of the expired air returning to the bag. In the Newcastle model the purifier is larger than that illustrated.

The ends of the tubes within the bag form a plug-and-socket connection, allowing them to be joined (as indicated by the dotted lines of Fig. 21) should the bag be torn during use.
An attachment \( F \) is provided, consisting of a length of flexible tube ending in a mouthpiece and relief valve. By connecting this tube to \( R \) it may be possible during the first part of a two hours' interval to supply air to another man in the manner shown by Fig. 20.

The Tissot Apparatus.—Dr. Tissot's apparatus, well known in France for mine and army purposes, is illustrated by Figs. 22 to 25. The apparatus is carried altogether at the back, though the pressure gauges \( G, g \) are placed so as to be visible to the wearer. The purifier \( P \) and breathing bag \( B \) are within the case \( K \). The single oxygen cylinder \( C \) has a valve wheel \( V \) within easy reach of the right hand. The Tissot differs from all other rescue apparatus of the present day in that purification of the air is effected by potash solution in place of solid alkali. During transport, the solution may do harm by entering the tubes; so the apparatus is carried empty, and the lye is prepared immediately before use. Small boxes of solid caustic are supplied, each holding sufficient for one charge. The contents of a box are dissolved in 1.05 litres of water, and, when cool, the solution is poured into the purifier, one-third going into each of the three compartments through which the vitiated air has to circulate. Caustic solution has the advantage of reducing the heating of the air; but it is troublesome in preparation, is attended by the risk that the solution may be carried up into the mouth while the wearer is crawling, and—as Tissot has applied it—is not particularly effective in abstracting \( \text{CO}_2 \). The original Tissot apparatus was intended purely for nasal breathing—tubes, first wetted with saliva, being thrust into the nostrils. A later model (1908) had a mouthpiece attachment in addition to the nasal tubes. In the form illustrated the nasal tubes are abolished and all breathing is by the mouth, the nose being closed by a clip supported by a strap which passes round the head and which is connected to rings over the ears (see Fig. 23). The abandonment of the nasal tubes was due to their discomfort and difficulty of adjustment. They made a blow to the apparatus very painful. Moreover, it was found that the irritated mucous membrane of the nostrils swelled and, by obstructing the tubes, could lead to suffocation. The valves in the metal portion of the mouthpiece are hinged clacks of brass. The short chain seen in Fig. 23 immediately under the mouthpiece is used in emptying the saliva trap at intervals of about 15 minutes.

Tissot was the first to control the oxygen feed by means of an adjustable reducing valve manipulated by the wearer. In Fig. 24, \( R \) is the reducing valve and \( D \) the adjusting screw. \( G \) is the main pressure gauge registering the reserve in the cylinder, while \( g \) is a second gauge interposed between the reducing valve and a fine orifice through which the oxygen passes to the breathing circuit. The gauge \( g \) can thus be made to record the oxygen discharge. On the face of gauge \( g \) are four marks, the first indicating "Rest," the second "Marching," the third "Work," and the fourth "Aid." The wearer turns the screw \( D \) until the needle of \( g \) stands over that one of these four marks which accords with the nature of the work he is about to perform. The first two marks call for no explanation. The needle is brought to the third mark when specially heavy manual labour is to be performed, or when the wearer is about to climb a road of heavy gradient. The extra delivery afforded when the pointer is brought to the fourth mark is only taken advantage of when the wearer gets out of breath, when the bag flattens from a momentary shortage of oxygen, or when assistance is being given to facilitate the escape of a second man whose oxygen cylinder is exhausted. In the last circumstance the oxygen discharge pipes of the two apparatus are connected by a length of tubing.

The automatic relief valve \( E \) (Fig. 25) is novel in that it is a slide-valve controlled by the degree of inflation of the bag \( B \). To the bag is attached the light wooden flap \( F \), which is hinged at its upper edge. The pulsations of the bag cause a to-and-fro movement of \( F \), which in turn is transferred to the slide-valve \( E \). A highly inflated bag causes \( E \) to travel sufficiently from its mid position to uncover an opening through which discharge takes place.

The Gibbs Apparatus.—Mr. W. E. Gibbs, of New York, has recently designed an apparatus which has received very favourable notice at the hands of the writers of the American Report. Garforth's principle of automatically controlling the discharge of oxygen according to the needs of the wearer has been utilised, but
FIG. 19.—AEROPHOR, CHARGING WITH LIQUID AIR.

FIG. 20.—AEROPHOR, USE OF AUXILIARY CONNECTION;
Fig. 22.—Tissot Apparatus, Back View.

Fig. 23.—Tissot Apparatus, Mouthpiece Attachment.
Fig. 26.—Gibbs' Apparatus, Front View.

Fig. 27.—Gibbs' Apparatus, Back View (cover removed).
instead of the discharge valve being actuated by pressure-difference, as in the Weg, it is here opened mechanically by the partial collapse of the breathing bag. Outwardly, and indeed, in general arrangement, the Gibbs apparatus resembles the Tissot. The single oxygen cylinder $C$ (Figs. 27 and 28), charged to 150 atmospheres, is connected to a pressure gauge $G$ and a reducing valve $R$. In the model received by us, the gauge (which is out of sight of the wearer) is of ordinary type; but the inventor intends it to be of a kind that can be read by touch. The reducing valve, of excellent design, is all of metal, the diaphragm being supported on a thin copper concertina of great sensitiveness to variations in pressure. The valve reduces the pressure to about one-sixth of an atmosphere. On leaving the reducing valve, the oxygen passes the safety valve $D$, which is set to operate at half an atmosphere, and which sounds a whistle on discharging. The whistle gives warning of a leakage at the reducing valve. The bag $B$ is of the bellows pattern. When it is three parts emptied, the lever $E$—weighted to maintain a positive pressure in the apparatus—comes in contact with, and opens, the admission valve $I$. Oxygen flows into the bag until the distension is such as to permit $I$ to shut. $E$ is a cooler of blackened copper. $V$ and $v$ are respectively the inhalation and exhalation valves. The lungs furnish the motive power to produce the circulation in the breathing circuit. The purifier $P$ is of special type, and will be dealt with fully in a subsequent Report. As described in the inventor’s patent specification the purifying medium is caustic soda cast upon gauzes which are arranged in parallel within the cartridge, and which are placed in an upright position so as to allow water or sodium carbonate in solution to drain readily from them. The apparatus is protected by a cover of aluminium. The illustrations are taken from the American Report, p. 22.

The Pneumatogen Apparatus.—Unlike any of the apparatus described above, Bamberger and Böch’s “Pneumatogen” regenerates the air by causing the products of expiration to pass through cartridges of oxylith (potassium sodium peroxide). This substance is attacked by CO$_2$ and watery vapour with the liberation of about the same volume of oxygen as the carbonic acid and water contain. The apparatus has hitherto not been successful owing to the development of excessive resistance and heat. The small weight of the apparatus is its chief advantage.

PART II.

RECOMMENDATIONS REGARDING RESCUE APPARATUS.

Official Approval of Breathing Apparatus.—We find that a high proportion of the criticisms of rescue station instructors and others qualified to judge are directed against structural defects in breathing apparatus for which the makers are entirely responsible. Some of these faults are highly serious, as, for example, where purifiers of defective arrangement or careless construction have been supplied, or where the apparatus as a whole has been essentially unsafe owing to faulty design. It seems to us that, as the Legislature has required the provision of rescue apparatus, official action should be taken to guard against risks of this character. In our opinion the best way of so doing is to prohibit the use of breathing apparatus in mines under the Coal Mines Act, unless the apparatus be “of a type for the time being approved by the Secretary of State.” The restriction should also apply to materials supplied for charging and repairing such apparatus. There would then be the same control over design and workmanship as now exists in the case of safety lamps.

Proposed Inspector of Rescue Training and Organisation.—In view of the special character of the organisation respecting rescue operations, and of the apparatus used, we are strongly of opinion that an inspector should be appointed under the Mines Department of the Home Office, whose function it would be to advise the Chief Inspector of Mines as to the safety of these apparatus, to see that the Regulations regarding rescue operations were properly carried out, and that apparatus at central stations, substations and mines were maintained in condition fit for immediate service. That part of the Regulations relating to ambulance could also be placed under this inspector’s supervision.
The Chief Inspector of Mines or an inspector in charge of a division should possess the power of directing that any apparatus in use at a rescue station, or any material supplied for charging or repairing apparatus at a rescue station, should be submitted for inspection and test.

If this proposal were carried out, the inspector would in course of time obtain an unrivalled knowledge of rescue appliances and cognate subjects, which could not fail to be of benefit to those in charge of rescue stations and of assistance when actual rescue or recovery work had to be undertaken.

Wearer of Apparatus should be capable of doing Hard Work.—It is commonly held that rescue apparatus is not meant for strenuous work, and instructors insist—and with certain present-day apparatus, or with defective methods of use, very rightly insist—on their men moving leisurely and taking work slowly while wearing the apparatus. It seems to us that these limitations themselves afford the best proof of the inadequacy of the apparatus to meet the exigencies of service. Underground, in the stress of an actual emergency, it is not always possible to avoid heavy labour when wearing apparatus. When it is a question of life or death, men will rightly take great risks, and no instructions will prevent them from so doing. Again, operations may be proceeding in an area of the workings lying to the dip, and to reach fresh air from such an area may involve travelling several hundred yards of incline in a strictly limited time. The brigade would be loaded with the apparatus and other impediments, and might in addition be carrying a person on a stretcher. From the respiratory standpoint it would be doing very hard work. The foremost requisite, then, of a safe and successful mine rescue apparatus is that it should be capable of protecting the wearer for at least two hours during any kind of work he may have to attempt. It should permit of the heaviest exertion during at any rate a part of that time, including the last part.

Causes of Failure of Apparatus.—The failure of an apparatus may be due to any of the following causes:—

The Accumulation of CO₂.—1. A dangerous proportion of CO₂ may accumulate in the air breathed.—With certain existing apparatus this is the commonest cause of failure. When the percentage of CO₂ in the air contained in the lungs exceeds about 10 or 11 a man begins to stagger about and lose consciousness; and a slightly higher percentage causes complete loss of consciousness. During considerable muscular work the danger point will be reached when the inspired air contains from 4 to 6 per cent. of CO₂, so that an accumulation to this amount, owing to failure of the purifying arrangements, is dangerous.

This failure may be due, either to the wearer rebreathing expired air which has never passed through the purifier, or to failure of the purifier to absorb the CO₂ passing through it. Of these causes the former will be considered first; it is responsible for many accidents, and is apt not to be properly appreciated. With the injector type of apparatus (Draeger and Meco) the amount of air circulating through the purifier is limited, and is often only about half as much as a man breathes during the heaviest exertion. The consequence is that with any considerable exertion part of the expired air has to be re breathed without purification, and great respiratory distress ensues. If either the injector or the purifier is working imperfectly loss of consciousness may easily result. (Also see p. 22.)

If the helmet form of apparatus is also used, expired air is necessarily rebreathed at every breath, and in greatly increased proportion during heavy work, so that the helmet is far worse in this respect than the mouthpiece, and is in the highest degrees dangerous with the limited air circulation given by existing injectors, as was pointed out in detail in the reports to the Doncaster Coal Owners’ Committee. With apparatus in which the lungs of the wearer drive the air through the purifier there is no appreciable rebreathing of expired air if the valves are efficient, and this source of temporary disablement or danger during any hard exertion is avoided.

Failure of absorption of CO₂ by the purifier may be due either (\(a\)) to an insufficient amount of absorbing material, or (\(b\)) to faulty arrangement of it, in which case serious proportions of CO₂ come through although plenty of absorbent remains unused. The pressure gauge informs the wearer as to whether he has still sufficient
oxygen, but there is nothing at present to inform him as to the state of the purifier; and if the purifier fails while the wearer is trusting to his oxygen gauge as an index of the reserve of safety in his apparatus the result may be fatal. There is no doubt that several men have lost their lives through failure of the purifier.

**Requirement as to Purifier.**—We are strongly of opinion that a purifier should be so constructed that it will outlast the oxygen supply. This can only be insured if the purifier is such that however much of the oxygen may be actually consumed by the wearer the purifier will still absorb satisfactorily the CO2 which he gives off. As a matter of fact many of the existing purifiers will not stand this test, and are therefore more or less unsafe. When a man of average weight is walking at a rate of four miles an hour on the level he absorbs nearly 2 litres a minute of oxygen, and gives off about 1.7 litres a minute of CO2. If the oxygen supply is set to the ordinary standard rate of 2 litres a minute he will then discharge into the purifier about the maximum possible amount of CO2. A simple and easily feasible test of a purifier is thus to see whether it will stand for two hours, or till the oxygen is exhausted, with the wearer walking on the level at four miles an hour.

We recommend that this test, which is practically that adopted in the Doncaster experiments, be taken as a standard test for a purifier. Even if the oxygen supply and rate of work are cut down, so that the oxygen lasts for several hours more, the purifier will still be efficient. The absorption of CO2 may be considered satisfactory if the proportion of CO2 in the inhaled air from the apparatus does not exceed 2 per cent. at the end of the test period.

**Failure of Oxygen Supply.**—2. *The Oxygen Supply may fall Short.*—When this occurs it is not usually owing to a deficiency in the original store of oxygen but to leakage. Leakage of oxygen may occur either at connections, or, when the helmet or face-mask is used and the oxygen supply is not constant, at the face-joint.

When oxygen is carried in cylinders the gauge informs the wearer as to the adequacy of the reserve supply both at the commencement and at any subsequent moment. The liquid air apparatus does not possess this advantage, and has to be safeguarded against failure of supply (a) by being charged with a weight of air well above the probable requirement, (b) by ensuring that the liquid air receptacle is properly insulated and packed, and (c) by taking care that the relief valve does not discharge too easily and that the purifier has little resistance; or else more air will be lost than can be spared during the later portion of the period of use.

**Danger of low Oxygen Percentage.**—3. *The Oxygen Percentage in the Air breathed may fall dangerously low.*—It may easily happen during extra hard exertion, as in going up an incline, that more oxygen is being consumed than the 2 litres per minute usually supplied. If the breathing bag of the apparatus has been filled with air to begin with, the consequence will be that the oxygen percentage in the apparatus may fall below that in normal air. Both practical experience in mines and the special tests made at Doncaster show, however, that no actual danger results, provided the rate of supply is about 2 litres per minute, the wearer simply becoming so much out of breath that he is compelled to slow down. If, however, the rate of supply is considerably less than 2 litres a minute, the wearer is very apt to lose consciousness before he realises his danger, and the results may be disastrous if he is in irrespirable air.

This risk attendant on a low rate of supply may be minimised if both the bag and the lungs of the wearer are washed out with pure oxygen at the start. The collapse of the bag will then provide a safe warning that the supply is inadequate, and time will be given to refill the bag through the by-pass, if there is one, or else to interrupt the exertion. But if the rate of supply is below 2 litres per minute and the oxygen is at all seriously contaminated with nitrogen, sufficient of that gas may have accumulated in the bag to entail a grave chance of consciousness being lost. When, however, the bag, and the lungs of the wearer, have been washed out with oxygen to begin with, as we advise on p. 27, and the oxygen is over 98 per cent. in purity, this danger can hardly occur until about 200 litres of oxygen have issued from the cylinders, unless some air has leaked in
at the mouthpiece or elsewhere. The troubles incident to impure oxygen will be discussed in detail on a later page.

Failure due to entry of Poisonous Gas.—4. The Apparatus may Leak.—Leakage of oxygen under high pressure has only one effect, namely, to reduce the time during which the apparatus may be used, and is indicated by an unduly rapid fall of the gauge. But the results of leakage in the breathing circuit are less simple and less easily detected. The possibility of noxious air being drawn into the current by the injector is dealt with more fully on a later page. The absence of the injector, however, does not entirely remove the danger of inward leakage. A hole existing in the mouthpiece attachment or in the tubes or connections near it may, in all types of apparatus, give rise to inward as well as outward leakage, while with the helmet or face-mask the risk is much enhanced.

Outward leakage, considered alone, leads to exhaustion of the apparatus, and to the possibility of the bag being drawn flat during work—a question discussed under the next numbered sub-head. Inward leakage in air containing CO has its obvious risks.

Provided there is a constant oxygen supply of about 2 litres per minute, inward leakage of blackdamp or firedamp not accompanied by a toxic gas, although undesirable, is not of great importance. However, in apparatus such as the Weg or Gibbs, such leakage—even though of fresh air—at, say, a point in the inspiratory tube, would be dangerous in that it might be the cause of the oxygen supply failing.

On p. 31 we describe how apparatus may be tested for leakage before it is put on. When testing, attention should be directed in particular to those parts subject to negative pressure, namely, the mouthpiece and inspiratory tubes.

The death of Mr. Lewis M. Jones while wearing rescue apparatus in exploring after an explosion at the No. 7 mine of the Jamison Coal and Coke Co., Barrackville, W. Virginia, imperatively shows the need for scrupulous care in testing the parts of an apparatus near the mouth. He fell a victim to CO, which in all probability entered the apparatus through a crack in the side of the rubber mouthpiece.*

It is important for rescue men to realise the special danger of a leak inward when the air contains carbon monoxide (afterdamp and gas from fires or spontaneous heating of coal). The carbon monoxide is gradually absorbed by the blood until its power of carrying oxygen is seriously diminished. The effect of this may not be noticeable so long as a man is doing little work, and particularly if there is nearly pure oxygen in the breathing bag; since when nearly pure oxygen is breathed the blood carries much oxygen in simple solution, independently of the carrying power (due to haemoglobin) which is weakened by the carbon monoxide. But as soon as the man begins to exert himself seriously as in ascending an incline, he requires all the normal oxygen-carrying power of his blood, and if this is much impaired by carbon monoxide he is apt to faint owing to insufficient oxygen supply to the heart. This liability is largely increased if the oxygen percentage in the bag diminishes owing to the oxygen supply being insufficient to meet the increased demand, and also to the simultaneous presence inside the bag of nitrogen which has leaked in along with the carbon monoxide, or has accumulated owing to the oxygen in the cylinder being impure.

The danger can be averted by going slowly; and a young and active man is more likely to be affected in this way than an older man, who is less apt to hurry. But the main point is to be most careful to avoid the leakage. A leaky mouthpiece is specially dangerous; and many lives have probably been lost owing to the use of helmets or face-pieces, and consequent leakage inward as well as outward.

Treatment of Person suffering from CO Poisoning.—The correct treatment of a person who has collapsed from carbon monoxide is exactly that which was applied—but unhappily without effect—by the deputy who went in to assist the two Newgate men (see p. 28), and he deserves every credit for his action. When he reached the unconscious men he restored their noseclips and mouthpieces, and, having assured himself that the apparatus were working satisfactorily, flushed out their breathing bags with oxygen. In brief, collapse from CO poisoning

* American Report, p. 90.
while wearing a leaky rescue apparatus is particularly apt to happen during accelerating muscular exertion, and the only treatment likely to be attended with success is to keep the patient breathing as pure oxygen as possible until he has been removed to innocuous air, and for some time after he regains consciousness. Oxygen apparatus should also be at hand for a long while afterwards, ready to be applied if unconsciousness should again supervene; and the patient must be kept warm all the time.

**Failure due to Flattening of Breathing Bag.**—5. The Inspiratory Breathing Bag may become so empty that a full breath cannot be drawn from it.—This is in practice a dangerous accident if it occurs suddenly, and has probably been the indirect cause of several fatalities owing to the panic it produces. Collapse of the inspiratory bag may be caused by a leak in the apparatus at a place where the internal pressure is positive. The most frequent cause, however, has been the action of the automatic blow-off valve on an expiratory bag, as in the Draeger apparatus, or on an expiratory tube, as in the case of the liquid air apparatus. With the excessive breathing induced by considerable exertion or by an excess of inhaled CO₂, the air has not been able to escape easily onwards from the expiratory bag or tube. The consequence has been that the escape valve has acted freely, and so much air has escaped that the inspiratory bag has been unable to fill fast enough, and has, therefore, collapsed rapidly. With an apparatus liable to this accident, any considerable exertion, or failure of the purifier, is evidently dangerous.

Collapse of the bag may also be caused by accidental pressure on the bag. This is specially apt to happen when the wearer is bending or crawling. In certain apparatus, such as the Proto, the design is such that the risk of collapse of the inspiratory bag is avoided entirely.

**Requirement as to Freedom from Resistance.**—6. The Apparatus may fail because of Excessive Resistance to Breathing.—(a) Resistance may be due to choking of the purifier, to sticking of the valves, to insufficient area of the air passages, or to the accumulation of water or (in liquid air apparatus) of ice in those passages. Whatever may be the cause of the resistance, the effect is to create a considerable difference in pressure at the mouthpiece between expiration and inspiration. Apart from the discomfort in breathing, the risks of leakage, both inwards and outwards, are greatly increased by resistance in the circuit. Even the mouthpiece is liable to leak in such circumstances. (b) A highly distended apparatus, due perhaps to the relief valve failing to operate, is uncomfortable to use owing to the exertion needed on exhaling, and, unless the pressure can be relieved, may lead to serious difficulty.

No apparatus can be considered satisfactory in which, while walking at four miles per hour, there is discomfort due to either of the above-mentioned causes of resistance.

**Requirement as to Temperature of Inspired Air.**—7. The Apparatus may fail owing to the Temperature of the Inspired Air becoming Excessive.—The capacity for work is greatly reduced and the discomfort of using the apparatus much increased by a high wet-bulb temperature. An apparatus should be regarded as unsatisfactory if the wet-bulb temperature of the inspired air exceeds 105° F. (40° C.) under the temperature conditions commonly met with in the mine. We propose in a subsequent report to deal more amply with this problem.

**Failure due to rise in Body Temperature.**—8. The Wearer of an Apparatus may be overcome by rise in his own Body Temperature.—This is apt to occur when the wet-bulb temperature of the mine exceeds 80° F. In some forms of apparatus the heat of the purifier may be a contributory cause. To minimise this danger unnecessary clothing should be discarded in hot mines, excessive exertion avoided, and protection afforded against conduction or radiation of heat from the purifier. It is important that, during training, men should experience the effects of high wet-bulb temperatures, and so learn how to escape risks from this cause.

**Constructional Requirements.**—9. The Apparatus may fail through faulty construction or material.—Only the best and most suitable material should be
employed in making rescue apparatus, and only the best workmanship and finish should be permitted. Individual parts should be correctly designed for the duty they have to perform. All metal surfaces intended to encourage radiation should be finished in dull black. Screws should be standard Whitworth gas thread. Gauzes should be so held that no part of them can become detached. Supply pipes and other fittings should either be fixed so as to lie close to the body, or should be enclosed so as not to be liable to get damaged or detached by contact with projections in the passages of the mine.

The apparatus ought to incommode the wearer as little as possible, particularly when he is in a stooping or crawling position. It should also permit free vision in that position.

The Helmet and Face-mask.—We are glad to find an almost complete unanimity among rescue station instructors in condemning the so-called helmet as an attack- ment to self-contained breathing apparatus. It suffers from the objections that it cannot be made an air-tight fit in all cases, and that, as already explained, it entails grave risk of the wearer being disabled by CO₂. These defects are so over- whelming that a discussion of the merits of the helmet would be a waste of time.

Recommendation to abolish existing Helmet and Face-mask.—The face-mask, which covers the nose and mouth, leaving the rest of the face exposed, is preferred by some instructors. We agree that certain of the better masks, such as that used with the Weg apparatus, afford some degree of security against leakage when the pneumatic joint is tight, the breathing easy, and the wearer's face smooth and well filled-out. We are obliged, however, to pay attention to the unfavourable rather than to the favourable subject; and, certainly, none of the face masks examined give proper security when worn by a person having hairy or sunken cheeks, or by one whose cheeks readily fall in when drawing breath against a slight resistance. The mouthpiece is the only attachment independent of such considerations, and the only one on which reliance can be placed. We recommend that the existing types of helmet and face-mask be abolished in so far as self-contained apparatus are concerned.

The Oxygen-feed.—In a subsequent report we intend to deal at length with the various matters bearing upon oxygen supply. Our purpose just now is to call attention to certain aspects of that question on which we recommend action without delay. These are the following:—

Preventing Main Valve being closed during Work.—The main oxygen valve should be so arranged that it is impossible for it to be turned off accidentally while the apparatus is in use. The necessity of this precaution was tragically demon- strated by the death of Captain Ramsay, Superintendent of the Elswick (Newcastle) Station, on June 6th, 1913. He died from oxygen starvation while wearing the Proto apparatus. The valve was found shut; and it is possible that it may have been closed by contact with the floor or supports of the drift in which a practice was being undertaken. A similar occurrence, though less serious, took place during recent (1917) tests of apparatus at Mansfield, the Proto again being worn, but without the safety catch supplied by the makers. The following extract, describing the incident, is taken from Mr. G. L. Brown's "Experimental Notes on Self-contained Rescue Apparatus," an MS. document submitted to the Committee through the kindness of the Directors of the North Midland Coal Owners' Rescue Station Company, Limited:—

"After about 85 minutes Broadbent had to be taken from the gallery for a few minutes, as he was on the point of collapsing when the instructor dashed in. His oxygen supply was found to be cut off, the valve being closed. He stated that he did not turn the supply off, so that it must be concluded this happened accidentally, probably by one of the bricks he was carrying. He may have been trying to save his oxygen by closing the valve occasionally."

We have record of several cases of men, on starting a practice, turning off the oxygen under the impression that they were turning it on; and in the American Report (p. 39) three instances are noted of men forgetting to open the oxygen
valve before closing the apparatus and applying the noseclip. When the bag is properly flushed out with oxygen at the start accidents from these causes cannot occur.

_Figs. 29 and 30._ Sunk Spindle Valve and Key for Sunk Spindle Valve.

**Sunk-spindle Oxygen Valve recommended.**—The handwheels of the main valves of the latest Proto and Draeger apparatus are fitted with locking contrivances to prevent accidental shutting of the valve and another locking contrivance designed by Mr. Macaskill is in use at the Doncaster rescue station; but we think that the adoption of the sunk-spindle valve, one design of which is shown in Fig. 29, would result in a more complete immunity from the occurrences referred to above. This compact and simple fitting has given good results at the Edinburgh Station. The key (Fig. 30) is double ended. The box-spanner serves to turn the square-ended valve spindle S, while the jaw-spanner is required when tightening or slackening the screw-cap C. The latter prevents the escape of oxygen should there be leakage along the spindle—a common defect.

**Danger of insufficiently opening Valve.**—The men should be warned against opening a main valve insufficiently. A fraction of a turn may be enough to release enough oxygen under 120 atmospheres pressure; but when the pressure has sunk a good deal the flow may be checked if the valve is left in that state. The cock should always be opened wide.

**Unsuitable Design of Proto Valve.**—The main valve of the older Proto apparatus compares unfavourably with that of the latest form or with the Meco or Draeger valves, it being possible, with the first, to continue unscrewing until the valve spindle is withdrawn, when all the oxygen is at once lost. The locking chain and spring hook fitted to the Proto was originally applied by Mr. W. Clifford, of...
the Stoke-on-Trent station, as a means of preventing the valve being rotated more than a safe number of turns when it is being opened. It would be preferable, however, to refit all these apparatus with valves of better design. A further drawback of the older type of Proto valve lies in the use of a stuffing-box round the spindle. This form of gland is difficult to keep tight. These remarks also apply to the by-pass and pressure gauge valves of the Proto apparatus.

The new Proto and the Meco and Draeger valves are almost identical. That shown in Fig. 29 is a Meco valve. The valve proper, V, and the short square rod, R, are the only portions with up-and-down movement. The spindle merely rotates. The flat fibre washer, W, takes the place of the stuffing-box of the original Proto form; moreover, it is only possible to unscrew a few turns, i.e., until the valve moves up against the bottom of the spindle.

**Insufficient Oxygen Supply at certain Proto Stations.**—The majority of self-contained apparatus depend upon a uniform oxygen feed which is not under the control of the wearer. In all the cases that have come under our observation this feed has been adjusted to be about two litres per minute, with the exception of certain Proto stations where a lower rate of feed has been adopted, the by-pass being used to re-inflate the bag should it become exhausted. Evidence, however, goes to show that at these stations, during gallery practices at any rate, the additional quantity supplied by the by-pass is relatively small, it being usual to find the cylinders half full after two hours' service.

**Oxygen consumed in Climbing Underground Inclines.**—Drs. Haldane and Briggs have made measurements in the mine of the amount of oxygen consumed by men carrying rescue apparatus while climbing inclines but breathing ordinary air. The results will be given in full in the Second Report; but it is advisable to state here a few averages in order to show how markedly the consumption may differ in actual operations from that in a training gallery, as exemplified by the case under notice, and how risky unduly low feeds must be. The oxygen volume used is expressed in litres per minute at 32° F. and 30 ins. barometer:

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<tr>
<th>Gradient of Roadway</th>
<th>Average Speed</th>
<th>Average Oxygen Consumed</th>
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<td>Miles per Hour</td>
<td>Litres per Minute</td>
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<td>1 in 6½</td>
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<td>1 in 3½</td>
<td>1·62</td>
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It is important to realise the nature of the experience which has resulted in dangerously low feeds being adopted at some Proto stations. They were not introduced merely to save oxygen, but because the men find the apparatus more comfortable to wear when the feed is low. The greater comfort is partly due, it is claimed, to the less highly distended state of the breathing bag, and partly to the reduced temperature of the inhaled air. The latter effect can only result from a decrease in CO₂ absorbed, and this again from a decrease in CO₂ exhaled. There is only one way of reducing the volume of CO₂ discharged by the body, and that is to do less physical work. In other words, by setting the oxygen feed at a low figure the amount of work it is possible to perform with the apparatus is restricted, and thus the temperature of the air is kept down. Obviously, it ought not to be necessary to have recourse to such an expedient to make the air cool enough to breathe with comfort. The Proto apparatus, however, is particularly prone to overheating.

**Proto Apparatus: Automatic Relief Valve advocated.**—The unpleasant degree of distension of the breathing bag which follows from a 2-litre oxygen supply during gallery work (much of which is light in character) is a complaint peculiar to users of the Proto apparatus. In the other types adopted in this country the relief valve opens automatically when the pressure within the apparatus reaches 4 inches of water, or thereabouts; but the blow-off of the Proto is actuated by hand. We believe that it would add to the comfort of the Proto apparatus, and
remove one of the temptations of adjusting the oxygen feed too low, if the relief valve were made automatic in action. Owing to the presence of the caustic at the bottom of the bag, there is little fear of its being squeezed so flat that the wearer will be unable to draw breath.

Constant Feed Apparatus: Minimum Feed prescribed.—In view of the fact that rescue apparatus, if satisfactory, must be such as to enable a man to attempt hard work without risking oxygen starvation, we advise, in the case of any breathing apparatus dependent on a uniform oxygen delivery, that it should be made illegal to adjust the reducing valve to supply less than 2 litres per minute.

Death of Hugh Doorbar at the Podmore Hall Colliery Disaster.—The combined result of an insufficient oxygen delivery and of the presence of nitrogen in the apparatus has recently been tragically demonstrated. Hugh Doorbar, the captain of a rescue team, died while wearing a Proto apparatus in the operations following the Podmore Hall explosion in January, 1918. The post-mortem revealed that death was due to CO poisoning. The apparatus was sent to Dr. Briggs, who tested it and reported to the Chief Inspector of Mines. The following is a brief account of the examination:

The reducing valve was found to be out of adjustment. Instead of delivering 2 litres of oxygen per minute, it gave 1.56 litres at a cylinder pressure of 120 atmospheres and only 1.17 litres when that pressure had fallen to 35 atmospheres. Information was to the effect that it was the practice in the district to inflate the bag, on starting, by taking a breathing of air through the nose and respiring into the apparatus. The degree of risk attaching to a low oxygen feed when combined with nitrogen in the circuit, and the suddenness with which the danger point is reached, were exemplified by an experiment with the Proto apparatus, fully charged with caustic sticks, and given an oxygen supply of 1.5 litres per minute. The wearer (Dr. Briggs), after inflating the bag with expired air, commenced walking to and fro on a concreted path. At the end of five minutes his respiration suddenly deepened and almost immediately he began to stagger and turn blue in the face, and had to be stopped. The reducing valve spring of Doorbar's apparatus was too weak. After strengthening the spring by placing washers above it, the valve operated normally and efficiently, discharging a constant volume per minute at any cylinder pressure between 120 and 15 atmospheres.

The main oxygen cock was also defective, it being impossible to close it completely even with the assistance of a tool. When merely screwed up by hand, unassisted by a tool, the valve discharged noiselessly but quite rapidly. If the valve was capable of being turned by hand a good deal of oxygen must have been lost before Doorbar put the apparatus on. The tests led to the following conclusions:

1. With the apparatus as received, inflated at the start with ordinary air, the wearer would run the gravest risk of sooner or later falling unconscious from oxygen want. If this were to occur in afterdamp, and, if in falling, the wearer should knock off his nose-clip, he would soon die from carbon monoxide poisoning. He would die still more quickly if the atmosphere were pure firedamp or black-damp.

2. The deficiency of the oxygen feed was due to the wrong adjustment of the reducing valve. The reducing valve was well designed and in all respects suitable, but it was not rightly adjusted.

3. The rapidity of collapse was probably due to the combined influence of the wrongly adjusted reducing valve and the leaky main valve of the oxygen cylinder. The latter allowed oxygen to escape and therefore let down the pressure, and the former gave a smaller and smaller feed as the pressure sank. The main valve was, as a matter of fact, of a type not well adapted to dealing with gas under high pressure—a defect which the makers are now remedying by substituting a valve of more satisfactory design.

The Injector: General Considerations.—In the Draeger and Meco apparatus the circulation of air is induced by an injector. This gives a constant flow independent of the breathing, but limited in amount. With the helmet an arrangement of this kind was practically a necessity on account of the large space in
the helmet, and the hopelessly impure nature of the air which would occupy that space but for the clearing effect of a current independent of the lungs. As has already been pointed out, however, this was at best a dangerously inadequate makeshift, since, during considerable exertion, the circulatory volume was quite insufficient.

With the abolition of the helmet the need for the injector disappears, as the lungs themselves can now provide perfectly for the air circulation. Indeed in mouthpiece apparatus the injector exists as a "vestigial structure" and, as is often the case with such survivors, it is responsible for more risks than benefits.

It has been claimed as an advantage of the injector that there is cooling of the air as it passes the injector, owing to the expansion of the oxygen as it leaves the nozzle. This effect is actually present, but is quite small in magnitude.

An injector which was adequate in all circumstances, and which never got out of order, would be able to make breathing a little freer; but the idea that it would be of great advantage appears to rest on imperfect physiological knowledge. The lungs are so controlled that they are able easily to deal with the very moderate resistance of a properly designed purifier circuit. When that resistance is encountered the respiratory muscles act more powerfully, so that the amount of air breathed is just as great as without the resistance, both the volume of air breathed and the force and depth of expiration being regulated by the percentage of CO₂ in the air of the lungs. With existing injectors the whole physiological object of breathing is defeated as soon as the volume of air breathed becomes greater than that circulated by the injector; and the result of this is often most dangerous.

Duchy Colliery Accident.—Nothing can better illustrate the great risks associated with a faulty apparatus than the accident at the Duchy Colliery, South Wales, in March, 1917. The circumstances, which were fully investigated at the time and reported on by Dr. Haldane, were as follows:—

A brigade wearing Draeger apparatus had gone up about 90 yards of an old incline in the upper part of which the air was extinctive to oil lamps, owing to the presence of a form of blackdamp which was only slightly heavier than air. The ventilation of the road was thus very sluggish; but, to judge from tests made afterwards, the air where the accident occurred was quite respirable and not extinctive to an acetylene lamp. The men moved very slowly, as they had been carefully trained not to exert themselves too much. One of them (Evans) seems to have gone a little too fast, and fell unconscious from the effects of CO₂. The rest were unable to make the exertion necessary to help him and only got down with difficulty. The instructor, Mr. Edward Thorne, wearing a Draeger, then went up with a fireman without apparatus and two fresh Draeger men. One of the latter was partly overcome while ascending and had to be brought back by the fireman. In two or three minutes after reaching Evans, Mr. Thorne fell over unconscious. His companion was so exhausted that he could give no help, but managed to get down. Again and again gallant attempts were made to rescue the two men, but the defective apparatus made these efforts vain; and no one went up without an apparatus as the air was believed to be irreparable. Both men died when their oxygen cylinders ran out. Their mouthpieces had been seen to be in place shortly before the oxygen finished, and although they were off when the men were found dead they probably were not disturbed until the final convulsions. The fatal results were due partly to defects of the injector arrangement, and partly to faulty purifiers. When tested afterwards, the cartridges still rattle, so they were not exhausted. They were, however, not filled in the proper manner and therefore allowed some CO₂ to pass. The apparatus acted satisfactorily during rest, but when the wearer (Dr. Haldane) walked at 4 miles per hour he was staggering from CO₂ poisoning within three minutes. The circulation within the apparatus was then much less than the volume of air breathed, so that CO₂ rapidly accumulated in the air inspired (see p. 23). With a fresh cartridge of the same kind the wearer (Mr. Macaskill, Doncaster Rescue Station) was able, with great distress and staggering towards the end, to walk at 4 miles per hour for 15 minutes, but afterwards developed a severe headache and felt ill for the rest of the day. Within 2½ minutes of starting there was 5·2 per cent. of CO₂ in the inspired
air, and 5.8 per cent. after 15 minutes. The air he was breathing was mostly returned directly from the expiratory to the inspiratory bag through the opening provided to avoid the risk of the latter bag being sucked flat.

Disadvantages of the Injector considered in Detail: Negative Pressure.—

The injector is liable to create a negative pressure behind it, the effect of which is to cause an inflow from the outer atmosphere if there should be a leak in the negative pressure zone. One death has resulted from this cause.* By altering the position of the injector Draeger has, in a recent design (Fig. 10), succeeded in placing the absorption cartridge in the positive pressure part of the circuit.† This is an improvement; it considerably reduces, but does not entirely remove the danger in question. A variant of the Meco apparatus, known as the “positive pressure” type, is also on the market.‡ In this form an auxiliary bag is introduced, at the back of the wearer, and in connection with the metal cooling pipe leading to the injector. No dependence can be placed on this arrangement as ensuring positive pressure. The auxiliary bag only acts as a rough kind of pressure indicator. When distended—which, in actual use, is seldom—there is certainly positive pressure throughout the circuit; but its distension cannot be observed by the wearer, nor have we ever met a trained man claiming to be able to feel the distension through his clothing. To place a bag—of all things the one most liable to leakage—in the very part of the circuit where leakage is most likely to have fatal results, is adding to the danger instead of diminishing it, and such a bag should never be used.

Risks of insufficient Circulation.—If the flow were always maintained, and if the purifier always acted perfectly, 50 to 60 litres of pure air per minute would be ample for the most exacting work the wearer is likely to be called upon to perform with rescue apparatus; but if it should sink to say, 35 litres, as has often been observed, it becomes insufficient for hard exercise. The circulation may fall to the vicinity of the latter figure owing to incorrect setting of the reducing valve, to the partial clogging of the secondary nozzle, to leakage from the circuit, to the accumulation of water or other material in the pipes, or to an increase in the resistance of the purifier. Even though it may prove up to standard at the start, the circulation usually diminishes—and sometimes diminishes considerably—during a practice.

Had one been dealing with pure air the problem would resolve itself into getting some effectual guarantee that the circulation never fell below a stipulated figure, say, 45 litres per minute; but it is unfortunately complicated by the influence of CO₂ upon the tidal volume demanded by the lungs. This influence is so marked that an air circulation which is enough when the air is pure easily becomes insufficient when the cartridge begins to fail.

When the wearer of an injector apparatus fitted with inspiration and expiration valves requires a greater air-volume than the injector supplies he exhausts the inspiratory bag and overfills the expiratory bag; breathing becomes more difficult, until eventually the inspiratory bag flattens in mid-breath. The sensation of the lungs being checked in this manner is extremely distressing and is apt to produce panic, and such an occurrence has to be prevented at all hazards.

The Meco and Draeger appliances must now be examined to see how they guard against this danger of an over-driven apparatus. The former attains its object by omitting both inspiratory and expiratory valves, thus putting on the injector all the responsibility of maintaining the flow. The bag on the exhalation side cannot now be overfilled at the expense of that on the inhalation side, there being nothing to prevent a readjustment of pressure between them by back-surfing of the air. Even if overdriven, breathing can go on, the lungs being partially filled by exhaled air reinhaled. In most of the patterns of Draeger apparatus used in this country the two compartments of the breathing bag are connected by a narrow

† British Patent No. 4378. 1913.
‡ Trans. I.M.E. xlv., p 230.
passage (p., Fig. 10). Provided the pressure in the inhalation compartment exceeds that in the exhalation compartment (which is the normal case), the flow in this passage is in parallel with that going to the lungs; but when the apparatus is overdriven the pressure in the exhalation bag becomes the greater, and some air from that bag returns through the passage to prevent the inhalation compartment being sucked flat. In another Draeger design the passage between the bags is omitted but the expiratory valve is left out, thus allowing the lungs to fill themselves from the exhalation bag if the circulation is insufficient.

We look upon these expedients with the gravest suspicion. All three of them are alike in that unpurified air is used to make up the indrawn volume when the lungs' demand exceeds the injector's supply. Consider what happens with an apparatus of this kind if provided with an inadequate purifier. As soon as the cartridge begins passing CO₂ the breathing automatically intensifies; a greater proportion of the volume in circulation passes into the lungs and the air delivered to the cartridge becomes richer in CO₂. These effects become more and more marked until the lungs need more than the injector can supply. At this critical point relief is given by adding expired air to air already dangerously charged with CO₂, with the result that the moment of complete failure approaches at an accelerating rate and unconsciousness may rapidly supervene.

The elimination of both valves in the Meco apparatus has the same effect as a large deadspace, for even with gentle exercise the lungs send back a part of the expired volume into the inspiratory bag, from which it passes to the wearer on the next inhalation. Similarly, with that type of Draeger in which the expiratory valve is omitted, an indrawn breath is always more or less polluted with vitiated air drawn back from the expiratory bag. These two latter methods of preventing the inspiration being sucked flat are particularly objectionable; at one and the same time they reduce the margin of safety and the amount of exertion possible to the wearer. No injector contrivance is safe from the serious danger under discussion unless it is so arranged that the lungs can at all times get the volume they require without having to draw upon unpurified air. Both inspiratory and expiratory valves must be present, and it must be made impossible for any air to reach the lungs without having first been through the purifier.

Injector Apparatus: Risk of withdrawing Mouthpiece.—If a man wearing an apparatus should trip and fall—as he is particularly liable to do when walking in smoke—his mouthpiece may be knocked out, and it may be a few moments before he recovers himself sufficiently to get it back again, or—in a more serious case—before his comrades can do so.

Mr. J. H. Thorne, of the Porth Rescue Station, called our attention to a third drawback of injector apparatus, namely, that if the mouthpiece be withdrawn the injector will suck some of the outside air into the apparatus.

Such a risk, certainly, does not exist with lung-operated apparatus, like the Proto or Weg, where the removal of the mouthpiece merely causes an outflow from the bag until atmospheric pressure is restored.

In order to ascertain the extent of the danger in question, a Meco apparatus was placed with its open mouthpiece in an atmosphere containing 2·73 per cent. of carbon monoxide, samples being drawn from a tap on the inhalation tube at intervals of 1, 2 and 4 minutes after starting the oxygen supply. These samples, respectively analysed 0·30, 0·36 and 0·41 per cent. of carbon monoxide, indicating a serious contamination of the air within the apparatus.

Choking of Injector.—The injector suffers from a further drawback in its liability to become choked. Most instructors at Meco and Draeger Stations—particularly at the former—have experienced this trouble, and if it occurred in irrespirable air the result would probably be fatal. The secondary nozzle and openings thereto occasionally get choked with dirt or caustic particles carried along the air passages. While interfering with the efficiency of the injector as a pump, such an occurrence rarely checks the oxygen feed. When the inner nozzle is blocked, on the other hand, the material obstructing the passage is generally found to have come from the reducing valve side. A very small particle is enough
to stop the hole. A case is on record of a nozzle becoming completely blocked during use by a minute piece of metal from a gauze. The wearer of the apparatus fell unconscious.

To prevent rust particles and other small fragments entering the nozzle from the pressure side, a filter is interposed between the injector and the reducing valve. In the Draeger apparatus the filter is a disc of very fine gauze, the openings in which (measured by means of a microscope having a micrometer eyepiece) are 1/12 mm. square. The mesh is thus sufficiently fine to catch anything that could block the nozzle. The Meco apparatus, when correctly fitted, possesses a filter consisting of a tight plug of cotton wool, held between two gauzes and clamped firmly in place. This, again, is efficient. But there are at rescue stations a considerable number of Meco apparatus in which the plug has been omitted though the gauze discs are present. Now the average Meco nozzle is 0.3 mm. in diameter, while the gauze mesh measures 0.2 mm. in the clear. This apparent margin of safety, however, may not actually exist, as the microscope shows that the drill has not always left a clean hole, and that the actual orifice of the jet may be half-moon shaped or quite irregular. The following measurements relate to five Meco nozzles selected at random:

1. Half-moon shaped orifice; maximum width, 0.23 mm.; minimum width, 0.17 mm.
2. Clean round hole, 0.28 mm. diameter.
3. Clean round hole, 0.37 mm. diameter.
4. Irregular orifice, maximum width, 0.25 mm.; minimum width, 0.20 mm.
5. Clean round hole, 0.35 mm. diameter.

If it is borne in mind that the filter could not stop anything less than 0.2 mm., the highly dangerous nature of jets (1) and (4) is evident.

It must not be inferred that by removing the injector all chance of choking the oxygen supply is eradicated. That possibility exists with apparatus such as the Proto, which has no injector, but which, nevertheless, has a fine opening on the discharge side of the reducing valve. Of the two, however, the injector is more liable to choke; the orifice is longer and is smaller in bore.

Recommendations relating to Injector.—There is no gainsaying the fact that the injector, as an adjunct to breathing apparatus, is a grave source of danger. To do away with it entirely is the only satisfactory solution of the problems to which it gives rise. We recommend that it be abolished in all future rescue apparatus, and that existing apparatus be altered, as soon as practicable, to eliminate the injector.

Rusting of Oxygen Cylinders.—It having been suggested by Messrs. H. Rowan and J. Parker, of Cowdenbeath, that particles of rust carried into the reducing valve from the cylinder may choke the orifice of the valve and cause a stoppage in the flow of oxygen, an examination was made of the cylinders of three apparatus to ascertain the degree of rusting. Patches of rust were found in them all, but one, a Proto pair, was particularly bad. The latter had been suspected of being rusted up inside owing to the comparative slowness of discharge of the gas from it when the main cock was opened to free air. On removing the end connections, and cleaning these Proto cylinders in the manner shortly to be described, 6.3 grams of scale and rust were obtained, much of it being in a loose state. The passage in the iron neck connecting the cylinders being, in part, narrow in bore, the risk of the choking of that passage is evidently considerable. Several cylinders have been discarded at certain Military Proto Schools in France, because of the development of internal obstructions of this sort. Every time a cylinder is annealed more scale is made, and the danger in question is enhanced.

All apparatus fitted with a pair of cylinders have connections of narrow bore. So far as our own observations go, the Weg is the only one in which an attempt is made to prevent rust entering the connecting pipe. Into each cylinder of that apparatus there projects a tube, four inches in length, closed at its end but with

* South Midland Report, p. 45.
an opening at the side. The opening is covered with a fine gauze, which forms an effectual trap.

With the exception of the Weg, where the arrangement of the cylinders, one on each side, may be considered an essential point of design, the use of cylinders in pairs is a survival from the day when each cylinder had its own cock. The single cylinders of the Gibbs, Tissot, and new Draeger apparatus are decidedly preferable, obviating, as they do, the need for the narrow connecting passage, and thus greatly reducing the possibility of internal choking.

**Danger of Graphite in Valve Glands.**—The dust from the inside of a Proto reducing valve was examined under the microscope. It was found to consist mainly of particles of graphite which had entered from the valve glands. An accumulation in the reducing valve orifice of these particles, or of rust, in the manner suggested by Messrs. Rowan and Parker, is not by any means out of the question, and, were it to occur when the apparatus was being worn in irrespirable air, would probably lead to the loss of a life. On the outflow side of the Proto reducing valve there is a hole, 0.4 mm., in diameter, through which the oxygen discharges. In the case in point, this hole appeared clear when held to the light; but when placed under the microscope a flake of graphite was seen to be wedged across it in a very ominous manner. We have already (p. 19) referred to the unsatisfactory design of the Proto cocks; it is now seen that by making use of asbestos-graphite packing they introduce a special and unnecessary risk. They should be changed as soon as practicable for the newer variety of cock, which has no stuffing-box gland. Interposed between the cylinder and reducing valve of the Proto apparatus is a fine gauze, which greatly assists in preventing rust from the cylinders and graphite particles from the main cock entering the reducing valve; but the pressure-gauge cock is on the outer side of the filter, and thus there is nothing to stop graphite from the latter cock making its way into the reducing valve.

**Cleaning of Cylinders and Prevention of Rusting.**—A filter gauze, such as that alluded to in the last paragraph, will always be valuable as a safeguard; but we think that the best way of coping with rust and scale is to attack it at the fountain head and prevent its formation.

Every time a cylinder is annealed (unless the annealing be done in an oxygen-free atmosphere) some scale and rust is made. We recommend that, immediately after annealing, the cylinders should be scoured inside to remove oxide, and then given a coat of varnish or otherwise protected against corrosion. Several ways of securing the insides of cylinders will suggest themselves to the reader; the following method is simple and has proved satisfactory for straight cylinders:—The scouring tool consists of a steel rod, \( \frac{1}{16} \) inch in diameter and 10 inches long, to one end of which is attached 6 inches of bicycle chain. The other end is held in the chuck of a lathe; the cylinder is pushed over the rod, the whole of the chain being inserted within; and then the lathe is started. The chain, trying to fly out centrifugally, scours the inner surface of the cylinder effectively. An excellent varnish to use after scouring is made from the following recipe:—Gum Shellac, 1 lb.; Methylated Spirits, 1 lb.; Venetian Red,* 3 ozs. It is innocuous, adheres tenaciously to an iron surface and does not flake off. Moreover, we find that the cylinder connections and distance-pieces (Proto) can be soldered on without hurting the varnish. It is applied by pouring a little into the cylinder, swilling it round, and pouring it out, the cylinder being then set aside to dry until the varnish is quite hard. One such coat is sufficient.

The problem of rendering an iron or steel surface rust-proof has received a good deal of attention of late years, and it may well be that experience will eventually point to some other mode of protection as superior to varnishing.

**The Danger of Nitrogen in the Oxygen Supply.**—When the wearer of a constant-rate oxygen-feed apparatus, set to supply two litres per minute, is doing work (such as building a stopping or erecting a brattice) which involves only

* Ferric oxide, alumina, silica, calcium carbonate, magnesia, and combined water.
moderate respiratory exercise, the blow-off valve is frequently in action and the apparatus is being continually flushed out. But if heavier labour is performed, the demand for oxygen may equal or exceed the supply; in which case the relief valve ceases to discharge, and the wearer no longer has the benefit of the scavenging action of excess air. The nitrogen existing as an impurity in compressed oxygen now begins to accumulate in the circuit, and, unless the supply is in a high state of purity, the oxygen percentage in the air passing to the lungs may rapidly diminish, although the bag remain normally distended. If this action goes far enough, the wearer will suddenly lose consciousness.

To get rid of accumulated nitrogen is important in all apparatus of the regenerator type; it is doubly important in the case of apparatus (e.g., the Weg or Gibbs) in which the oxygen feed is automatically determined by the degree of deflation of the apparatus.

Before we pass to the consideration of the actual proportion of impurity present in the oxygen supplied to rescue stations, it is advisable to remark upon certain measures for relieving the danger under discussion:—

Clearing the Apparatus of Nitrogen.—In the first place it is a mistake to fill an apparatus that has just been put on with air drawn in through the nose and expired into the bag. The object should be to reduce the volume of nitrogen in the apparatus at the start and not to add to it. The wearer should, therefore, begin by sucking the bag flat and exhaling through the nose. The oxygen being turned on, and the mouthpiece orifice being closed by the tongue, the bag is then allowed to fill up. A deep breath is then drawn from the apparatus and exhaled through the nose. The nose is now clipped. In this way nitrogen is swept out from the apparatus and the lungs.

Discharging through Relief Valve.—Unless the relief valve automatically discharges from time to time as the work proceeds, it is advisable before attempting any specially heavy work to empty the bag by squeezing the air through that valve, then filling up afresh with oxygen.

The Oxygen By-pass recommended.—The by-passes fitted to the Proto and Weg apparatus are very useful in quickly filling the bag after it has been purposely or accidentally flattened, and thus they assist in lessening the danger incident to nitrogen accumulation. We find that the majority of instructors favour the provision of a by-pass. Those of the reverse opinion base their objection on the possibility of misuse. The drawback exists; but it is one that may be minimised by careful training. We believe that the merits of the by-pass considerably outweigh the objections to it, and we advocate its adoption on every apparatus taking its oxygen from a compressed source. Besides that already named, the by-pass has the advantages of providing, first, the means for supplying extra oxygen should the wearer be for a short time undertaking work requiring more than the reducing valve is giving, and secondly, an independent channel from the cylinder to the circuit, which, at a pinch, could satisfy the wearer's needs, and enable him to make good his escape if the feed through the reducing valve failed for any reason. The most suitable mechanical arrangement of the by-pass will be discussed in a later report.

Official Requirement as to Oxygen Purity.—The "Memorandum on Schemes of Training and Practice," in the Home Office pamphlet relating to Rescue Work,* states as follows: "Where oxygen breathing apparatus is used, care must be taken to ensure a high standard of purity in the oxygen used, and supplies, unless guaranteed by the manufacturers, should be tested by analysis. The Secretary of State is advised that it is not practicable entirely to exclude the presence of nitrogen, and that provided the nitrogen+ present does not exceed 2 per cent.

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* Mines and Quarries Form No. 72, 1915, p. 3.
+ The impurity in oxygen prepared by the liquefaction process, though spoken of as nitrogen throughout this Report, is mainly argon. In one analysis given by Morey (Journ. Am. Chem. Soc., 1912, XXXIV., p. 491), the impurity amounted to 3·1 per cent., of which 2·8 per cent. was argon and 0·3 per cent. nitrogen.
the safety of the users of the apparatus will not be endangered. Oxygen containing a greater amount of nitrogen than 2 per cent., or any other impurity would become a source of danger and could not be regarded as complying with the requirements of the Regulations."

The rescue stations buy their oxygen from one or other of the ten factories of the British Oxygen Company. On a label attached to each charged cylinder the Company guarantees the high degree of purity of the gas, the guarantee usually being to the effect that the gas contains from 98.5 to 99.5 per cent. of oxygen. Doubtless, before the war, this extremely satisfactory proportion was realised but, owing to the pressure of war orders, the Company has recently been unable to maintain that standard in several instances.

Deaths at Newdigate Colliery.—The question became conspicuous when Professor Sir John Cadman, analysing the oxygen used by two men who died at Newdigate Colliery, Warwickshire, while wearing the Proto apparatus (October 8th 1916), found it to contain only 96.8, instead of 98.5 per cent. as guaranteed by the makers.

"This impurity, together with fact of the apparatus being set only for 1 ½ litres per minute, apparently accounted for the distressing symptoms which occurred when the men were travelling uphill, probably causing them to tamper with the mouthpiece and noseclips respectively so as to breath more freely. The result was inhalation of carbon monoxide from which the men died." *

After investigating the oxygen supplied to other stations in the Birmingham area, Professor Cadman took the matter up with the makers and eventually succeeded in getting the supply back to its original purity, so far as that district was concerned.

Analysis of Oxygen Samples.—During our visits to rescue stations in the summer and autumn of 1917 samples of oxygen were taken on several occasions and these were subsequently analysed by Dr. Briggs. The results are tabulated below. The samples from Mansfield were collected over mercury by Mr. G. I. Brown:

<table>
<thead>
<tr>
<th>Rescue Station</th>
<th>Supplied from</th>
<th>Date of Supply, 1917</th>
<th>Percentage Oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aberaman</td>
<td>Cardiff</td>
<td>14th June</td>
<td>93.99</td>
</tr>
<tr>
<td>Abercynon</td>
<td>Cardiff</td>
<td>8th June</td>
<td>91.96</td>
</tr>
<tr>
<td>Altofts</td>
<td>Sheffield</td>
<td>July</td>
<td>99.84</td>
</tr>
<tr>
<td>Altofts</td>
<td>Sheffield</td>
<td>August</td>
<td>97.04</td>
</tr>
<tr>
<td>Crumlin</td>
<td>Cardiff</td>
<td>15th August</td>
<td>96.35</td>
</tr>
<tr>
<td>Edinburgh</td>
<td>Glasgow</td>
<td>4th September</td>
<td>95.71</td>
</tr>
<tr>
<td>Howe Bridge</td>
<td>Birkenhead</td>
<td>12th September</td>
<td>98.80†</td>
</tr>
<tr>
<td>Mansfield</td>
<td>Sheffield</td>
<td>26th June</td>
<td>95.76</td>
</tr>
<tr>
<td>Mansfield</td>
<td>Sheffield</td>
<td>22nd August</td>
<td>98.17</td>
</tr>
<tr>
<td>Newcastle</td>
<td>Sheffield</td>
<td>11th September</td>
<td>98.22</td>
</tr>
<tr>
<td>Newcastle</td>
<td>Sheffield</td>
<td>31st August</td>
<td>98.31</td>
</tr>
<tr>
<td>New Tredegar</td>
<td>Cardiff</td>
<td>21st April</td>
<td>97.01</td>
</tr>
<tr>
<td>Porth</td>
<td>Cardiff</td>
<td>July</td>
<td>93.67</td>
</tr>
</tbody>
</table>

It will be observed that only six of the fourteen samples analysed conform to the Home Office requirements as to purity. Out of fourteen other samples analysed by Mr. Graham at the Doncaster Coal Owners’ Laboratory in 1917 up to August only

† Electrolytic oxygen.
three conformed to the standard, and one contained less than 80 per cent. of oxygen. The situation here revealed is grave. The most perfect breathing apparatus is dangerous if supplied with oxygen as impure as several of the results indicate.

On receipt of these figures Mr. Walker wrote (21st September, 1917) to each rescue station to call attention to the necessity of analysing all oxygen supplied for rescue work in order to ascertain whether it is of the required purity, and suggesting that the analyses should be recorded in a book kept at the station.

Compulsory Analysis of Oxygen advocated.—Makers' guarantees not being sufficient at the present time, we recommend that it be made obligatory to analyse the oxygen from every cylinder supplied for use in connection with self-contained apparatus, whether at rescue stations or at individual mines.

Oxygen containing more than 2 per cent. of impurity should never be used in actual work or practices underground with the apparatus, nor in any situation where a member of a brigade is liable to get out of sight of the instructor; and compressed oxygen holding more than 3 per cent. of impurity should not be used for self-contained apparatus in any circumstances.* The Superintendent should endeavour to build up the emergency (two days') stock from the purest oxygen available. This is easily done when every cylinder's contents are analysed.

With lung-controlled apparatus, such as the Weg or Gibbs or apparatus in which the oxygen supply can be cut down by the wearer, additional precautions should be taken against the accumulation of nitrogen, and with such apparatus the purity should be over 99 per cent.

Special Oxygen Analysis Apparatus designed.—To remove any difficulty that may be encountered in getting analyses done speedily and economically, two forms of analysis apparatus have been designed expressly for testing almost pure oxygen. The Committee desire to record their thanks to Mr. J. I. Graham, B.A., B.Sc., Doncaster Coal Owners' Research Laboratory, who in co-operation with Dr. Haldane has produced the first form. The second form is due to Dr. Briggs. Particulars of these apparatus are given in Appendix II. The inventors have endeavoured to provide simple appliances that can be used by station superintendents who may not possess previous knowledge of gas analysis.

Electrolytic Oxygen.—The electrolytic oxygen generated at the Birkenhead and Wolverhampton Works of the British Oxygen Company is of great purity. An analysis of oxygen from the former works is recorded in the above table, and one of Wolverhampton electrolytic oxygen will be found in the Second Doncaster Report, p. 16. The latter is: Oxygen, 99.95 per cent.; hydrogen, 0.02 per cent.; nitrogen, 0.048 per cent. In the sample from Howe Bridge Station the hydrogen amounted to 0.10 per cent. Freedom from hydrogen is the most important consideration with this class of oxygen. Volume for volume hydrogen is more dangerous than nitrogen owing to the possibility of an explosive mixture being developed within the apparatus with the former gas. The excellence of the quoted analyses should not be accepted as proof of a general immunity from this risk at those stations supplied with electrolytic oxygen. The following is an excerpt from the American Report, p. 54. It refers, of course, to American sources of supply:—

"Some of the samples that have been gathered from tanks of oxygen furnished to the Bureau for use in apparatus have shown a hydrogen content of as much as 3 to 4 per cent. It has been found on test at the Pittsburgh Laboratory that a little more than one per cent. hydrogen in certain apparatus which was used to the limiting capacity for oxygen supply, caused the circulatory system of the apparatus to become charged with as much as 23 per cent. hydrogen at the end of a two hours continuous use."

This, it may be added, forms a violently explosive mixture.

Safe Limit for Hydrogen Proportion.—We do not think that oxygen containing more than one-half of one per cent. of hydrogen ought ever to be used for rescue apparatus. It is especially important that the superintendents of those stations supplied with electrolytic oxygen should analyse all oxygen received. It is not sufficient to accept a work's guarantee. Unless the oxygen percentage exceeds

* These remarks do not apply to liquid air.
90\%, the hydrogen proportion should also be ascertained. The results should be recorded in a book kept at the station for that purpose.

**The Influence of Cold on the Absorption of Carbon Dioxide.**—Experience with the use of Proto apparatus in wintry weather and experiments in the laboratory have made it clear that caustic soda, when cold, is only a tardy absorber of CO\(_2\). In British mines, it is true, the temperatures are usually such as make this fact of small practical consequence; yet in colder countries, or in military or fire-brigade operations, it may be necessary on occasion to guard against the effect of low temperature. To warm up the caustic, the wearer should, in such circumstances, inhale from fresh air and exhale through the apparatus for a few minutes before finally clearing out the apparatus with oxygen and starting to use it.

The influence of cold on the rate at which CO\(_2\) is absorbed deserves the closest attention on the part of designers of liquid air apparatus.

**Liquid Air Rescue Apparatus.**—We intend, in a later report, to deal at length with liquid air breathing apparatus. It is a subject to which a good deal of attention and experiment will be directed. The present, however, is a fitting time to notice the great strides that have been made in this form of apparatus, chiefly through the labours of Colonel Blackett, Mr. F. P. Mills (Newcastle Station) and Mr. E. Elliston (Rotherham Station). The apparatus now in use at Rotherham and the stations of Northumberland and Durham can indeed claim to be a safe and suitable type for mine rescue purposes. But progress has not been everywhere the same, and we were surprised to see still in use at one station, the radically imperfect apparatus supplied some years ago by Henry Simonis & Co., which proved so dangerous in the Doncaster tests. There should be no delay in making the comparatively simple alterations to these faulty appliances to bring them in line with the best practice.

**Testing Breathing Apparatus.**—Systematically and frequently to test apparatus is one of the best of safeguards. A thorough test should be made of every breathing apparatus at a rescue station or mine at least once a month. It is useful to keep a record of the tests, the apparatus being numbered to facilitate reference. The dates of replacements and repairs can then be traced, and special tendencies of any apparatus—for though they may be outwardly alike some give more trouble than others—can be kept continuously under observation.

**Pressure Gauges.**—In examining an apparatus the first thing done is to turn on the oxygen and read the pressure gauge. Several instances have been brought to our notice of the unreliability of the small gauges attached to apparatus. Obviously a faulty gauge not only vitiates this test, but also forms a serious source of danger during active work. Especially is this the case when the lower reading are in error or when there is sluggishness of movement at the low pressures.

![Fig. 31.—Appliance for Testing Pressure Gauges.](image)
Mode of Testing Pressure Gauges.—We suggest the installation at stations of the inexpensive and simple arrangement designed by Dr. Briggs and illustrated in Fig. 31. It allows of gauges \((g, g)\) being compared, six (or less) at a time, against a standard gauge \(G\), calibrated at the National Physical Laboratory, Teddington, to which place it should be returned for examination once a year. A small oxygen cylinder \(C\), charged to 120–150 atmospheres, is attached to the appliance and the oxygen turned on. After the gauge readings have been taken, some of the gas is exhausted by means of the tap \(T\), when the gauges are again compared. In this way any number of readings is obtainable between the initial pressure and zero. More elaborate apparatus for testing pressure gauges are described in Messrs. Schäffer & Budenberg’s catalogues. Their only objection is that of price.

Leakage Tests.—Various ways of making a leakage test have been described in the First Doncaster Report, p. 21, and Mr. A. T. Wimbourn’s book on “The Use of Oxygen Breathing or Rescue Apparatus,” p. 29. They are well known to instructors. By far the best test, however, is to immerse the whole apparatus in water with the oxygen turned on and with the mouthpiece closed by the thumb. As the bags become distended bubbles rise from faulty joints on the circuit, while leakage of high-pressure oxygen becomes evident at once. Before submerging the apparatus certain parts, such as the slings and bag-cover of the Proto and the padded belt of the Meco, should be taken off.

No apparatus should ever be used in poisonous air until it has passed this test. We suggest that a suitable receptacle, such as a collapsible bath, be added to the equipment of a rescue station so as to avoid delay and trouble in getting something to serve the purpose at a pit. Had this test been applied, it is very probable that the leakage in the regenerator and joints which led to the death of an instructor at Caedale Colliery, near Swansea, in 1912, would have been detected before the team went underground.

Measurement of Oxygen Delivery by Wet Meter.—All instructors are familiar with the drum wet meter. Provided this meter is filled with water to the correct level, and that it is not used for measuring currents beyond the capacity intended by the maker, it proves an accurate means of measurement.

Measurement of Oxygen Delivery by Resistance Gauge.—A simple form of gauge for measuring oxygen delivery on a principle suggested by Dr. Haldane, and put on the market by Messrs. Siebe, Gorman & Co., is shown in Fig. 32. It consists of a glass \(U\)-tube, the longer limb of which (4) is graduated in litres per minute of flow, while the other limb contains, at its upper end, a plug of glass wool \(B\). Water is run into the bulb \(C\) until its surface stands at the zero mark of the scale. \(D\) is a drain tube which permits of the water level being accurately adjusted and also of the bulb being emptied before the instrument is put away. When the tube \(E\) is connected to the oxygen delivery which is to be gauged, the gas has to run through the wool plug in order to make its escape from the hole \(F\). In passing through the plug it meets with a resistance which is almost directly as the gas discharges*: the resistance—as a head of water—is indicated on the scale, which thus gives a measure of the flow. These meters have been found to give extremely good results. This instrument is quicker to use than the wet meter since no time interval has to be observed. Care must be taken to prevent water being shaken into the glass wool.

Draeger’s Float Litre Meter.—Draeger introduced a simple and useful oxygen-discharge meter which is shown at \(D\), Fig. 35, where it is combined with other gauging appliances to be described below. It consists of an upright glass tube protected by being placed within a metal tube. An observation slot is cut out of one side of the latter. The glass tube is slightly conical in bore, the larger end being uppermost. Inside the tube is a light wooden bobbin or float, which is impelled up the tube by the stream of gas entering at the bottom. The higher the float rises the wider is the annulus between it and the tube. The float settles at a point in the tube at which the force of impact of the oxygen on its under surface is equal to its weight. The scale, in litres per minute, is etched on the glass, and the flow is recorded by the reading opposite the top of the bobbin. Owing to inequalities in the bore of the glass tube, each instrument has to be calibrated separately, and the graduation is very irregular.

* See Trans. I.M.E., LIII., p. 223, for discussion of this law.
Fig. 32.—Haldane's Litre-meter.

Fig. 33.—Briggs' Litre-meter.
FIG. 28.—GIBBS' APPARATUS, FLOW DIAGRAM.
Briggs' Litre Meter.—Fig. 33 shows in vertical section a litre meter which resembles Draeger's in that a moving bobbin $B$ serves as indicator, but which differs from the German form in having a uniform bore glass tube $T$ in place of a conical tube. It was designed to meet the present-day difficulty of getting conical tubes in this country. Concentric with the glass tube is the nickel-plated rod $R$, whose shape is that of a long wedge, the point being uppermost. The bobbin, which is of boxwood or vulcanite, has a central hole and slides up the rod. The higher the bobbin the greater is the area of passage through this central hole. The graduations (ranging from one to ten litres per minute) are etched upon the outer metal tube $A$. They are much more regular than in Draeger's pattern.

Periodical Test of Meters.—It is highly advisable that these flow meters should be accurate, or, if in error, that their correction should be known. They ought to be compared at regular intervals with discharges measured by displacement. Oxygen and not air must be used in checking these meters.

Testing the Relief Valve.—An automatic blow-off valve requires frequent attention, as its proper adjustment has a good deal to do with the successful working of a rescue apparatus. It is easily tested by connecting to a water-gauge one opening of the bag or tube to which it is fitted and blowing into the other opening until the valve operates. The gauge should then register about 4 inches of water.

Testing Injector Apparatus.—The injector of the Draeger and Meco apparatus is designed to induce a static pressure-difference of 4 inches of water when passing two litres of oxygen per minute. An indirect but useful mode of testing the oxygen discharge is therefore to attach a water-gauge to either the suction or discharge side of the injector and then to turn on the oxygen.

Most instructors very rightly insist on each member of a brigade applying the water-gauge test before donning his apparatus; but valuable though it is, that test is not in itself sufficient. A more detailed scrutiny should be made from time to time, and especially after the "automat" has been overhauled. Any of the four meters above described may be used in determining the oxygen feed, the delivery side of the automat being connected to the gauge and the suction side being closed by a screw cap.

Draeger's Bag.—A simple method of gauging the circulation of an injector apparatus is to use Draeger's graduated linen bag, of which a photograph is reproduced (Fig. 34). The breathing bag being omitted, the measuring bag (rolled up and empty) is attached to the inhalation side of the apparatus and allowed to hang freely. The injector is then made to draw air from the outer atmosphere, through the absorbent cartridge and connecting tubes, and deliver it into the measuring bag during a timed period. The mouth of the bag being then closed, the "slack" is rolled up, and the volume read in the manner indicated by the figure. This appliance may also be used in measuring the discharge in liquid air apparatus. As the bag is apt to become seriously leaky, it should be itself tested under water at frequent intervals.

Combined Testing Set.—The clever appliance illustrated in Fig. 35 forms a valuable item of equipment of Draeger and Meco stations. $A$ is an ordinary water-gauge whose use has already been described. $B$ is a second water-gauge, by means of which the pressure needed to make the relief valve blow-off can be ascertained. By aid of the Bourdon pressure gauge $C$, the reducing valve can be correctly set and the automatic safety valve adjusted to operate at ten atmospheres. The oxygen discharge gauge $D$ has already been described. The tube $E$ is for measuring the circulation. The mode of action of the circulation meter is the same as that of the oxygen meter. The conical glass tube of the former, however, is wider so as to offer little resistance to the passage of air through it. The graduations range between 30 and 75 litres per minute, and the top of the float is
the reading index. In two cases in which these circulation meters were tested against displacement they were found to be accurately graduated.

If, as we recommend, the injector is abolished, there is, of course, no longer any need for tests of circulation, except in the case of liquid air apparatus.

PART III.

THE TRAINING OF RESCUE BRIGADES.

Rescue apparatus, no matter how perfect, is useless unless worn by properly selected and thoroughly instructed men. We therefore consider the subject of rescue-station routine and organisation and the training of brigades to be of equal importance with that relating to the selection of suitable apparatus. In this part of the Report we discuss aspects of this subject, and point out where we believe improvement could be made.

We have remarked in the Introduction on the excellence of the rescue station we visited. The general arrangements are so good that criticism is disarmed. We think, however, that in some cases improvement could be brought about in the training galleries. The aim should be to make a gallery resemble the roadway of a mine after an explosion; neatness and regularity are therefore out of place and undesirable. The gallery at Wath-on-Dearne is excellent in this respect. The floor, which consists of broken shale, is made very irregular; zones of displaced and disturbed timber are realistically arranged; the walls are of brick, and the air in the gallery can be made hot as well as irrespirable.

Wood, as a material for the roof and walls of a gallery, is to be avoided; possible, owing to its weakness and to the difficulty, when the roof is of wood, of setting timber in the same manner as in the mine. Exit doors should not be numerous, and windows should be kept high and narrow so as to allow debris heaps being laid under them. The plan adopted at Wakefield Station of providing a dark underground practice ground extending under a large part of the premises, in addition to the usual gallery, is worthy of imitation. It adds to the variety of the tasks which a team may be set. It also helps to inspire the men with confidence in the apparatus by accustoming them to work some little distance from escape doors. Bare signal wires run throughout the underground and surface galleries, being connected to a loud bell in the observation court. This enables the signal code to be practised, and furnishes a means of giving warning if anything untoward occurs.*

Organisation for Rescue Training.—There are, at present, three ways in which a mine may comply with the Regulations relating to rescue training, and these are as follows:

1. The mine may be connected with a neighbouring rescue station maintaining a resident brigade;
2. The mine may be connected with a station at which there is no resident brigade, the brigades being altogether formed of employees of the mines; and
3. The mine may be unconnected with a rescue station, the whole work of training men and maintaining the necessary apparatus being undertaken at the mine.

Unattached Mines.—A considerable number of mines take advantage of two of these alternatives. Some are so situated that attachment to a central

* Since this paragraph was written Dr. Briggs has visited Chesterfield and seen the excellent underground training gallery there. It has been skilfully laid out to resemble mine walls and must prove most valuable.
Rescue station is impracticable; others lie within reach of a central station but are unconnected with it, either because the owners are not members of the Coalmasters' Association controlling the station, or because the owners consider that pecuniary or other advantages accrue by dealing with rescue training themselves. We are aware of cases of unattached mines at which rescue instruction is of a high standard; but they form a minority. Instructing brigades, practising trained men, and maintaining apparatus are specialised operations which can be conducted more efficiently at a central station than at individual mines. Unattached mines within range of a central station are a source of weakness and possibly of danger, for, if a serious disaster befell the mine, the station could not refuse its assistance; it would then be required to co-operate with men whose efficiency would be an unknown quantity and whose apparatus may differ from the station equipment. If a central station is in existence we consider that no coal mine within the 10-miles radius should be permitted to remain unattached to it. The inclusion of non-members' collieries within the system of service of an Association rescue station need present no special difficulty. Some stations have already made the arrangement, a higher rate of subscription being generally charged.

Rescue Station Organisation: The Choice of Systems.—Opinion among instructors and others is divided upon the question as to whether the resident brigade system is to be preferred to the system of non-resident brigades. As a matter of fact that question hardly admits of a general answer, for it is considerably influenced by the size of the station's district and the character of the mines in that district.

There is no doubt that, when the district is large, the permanent brigade system gives the station staff less work, since the number of men drawn from the mines for training is then small. Indeed, in a few of the most populous districts, to train under the older non-resident system would involve such continual heavy work at the station that the teaching staff would have to be much increased to cope with it, and the wear and tear on apparatus would be correspondingly heavier.

A resident brigade becomes more familiar with the apparatus than does a colliery brigade. This is owing, not to any difference in the original course of training, but to the infrequency of the practices of the colliery brigade after its training is completed.

Medical and Physical Examinations of Brigade Members.—It is fortunate that the rescue squads are enlisted from men who, in the main, are used to hard manual work, and who are in good condition. There are, however, a number of semi-sedentary occupations connected with mining from which men have been enrolled. We have no desire to place obstacles in the way of such men joining the brigades; but we think it advisable to indicate a suitable manner of testing whether they are fit for the duty. Experience in connection with army medical examination has revealed the existence of a noticeable proportion of men in the general community whose organs are sound but who break down utterly under the stress of exertion. It has, indeed, been found that, invaluable though detailed examination for organic disease or weakness must always be, a further highly useful test in eliminating unsuitable subjects is to make the man do a spell of hard labour, either on the ergometer, or in running or stair-climbing, noticing how he supports the exertion, and particularly how he reacts after the spell is over. At present, the only test of suitability for a would-be brigade member is that he shall be examined by a doctor who certifies as to his condition. We suggest that, in addition to that examination, the applicant should undergo a physical test such as we outline above, and satisfy the instructor of his physical ability before the course of training commences. The chief technical officer at a rescue station should, we think, have power under General Regulations of rejecting any person whom he considers physically, mentally or temperamentally unsuitable for a place in a rescue team, even though the person should possess a medical certificate to the effect that he is organically sound.

He should also have power to discharge from a team a trained man should age, illness or accident make the trained man unfit to continue as a brigade member;
and it would be a safeguard if every member of the rescue team or corps were medically examined once a year.

In some districts the medical examinations are made by local doctors, while in others an independent doctor undertakes all such examinations at the station itself. We prefer the latter plan. It affords a juster and more uniform standard and centralises the responsibility. Moreover, it facilitates co-operation between the medical man and the instructor; and that is entirely desirable.

Age Limits of Men selected for Training.—The rules in vogue at many stations specify lower and upper age limits for rescue men, and some such limits could with advantage be generally imposed. Too young a man in a brigade may be a source of danger to himself and to the team through lack of discretion and steadiness. Twenty-three years (an age for which the Coal Mines Act itself provides certain precedents) might be accepted as the lowest for an acting member of a rescue brigade or corps. There is no objection to a younger man receiving training, if physically fit, provided that he is not enrolled as a brigade member until 23. Cure must be taken not to close the door upon university or college students, or upon intending applicants for the manager’s certificate of competency who may desire to undergo training for the purpose of gaining a practical familiarity with rescue apparatus. We do not think that a man over 45 years of age should be accepted for training in a brigade or corps, nor that an ordinar member should remain in the brigade after he reaches 50 years. Mine officials, however, and especially such officials as under-managers and oversmen serving as captains, should, if active and physically fit, be allowed to remain members of brigades even though over 50, owing to their great value as leaders. It is far better to keep such men at work in their task than to dismiss them from the service and introduce new members who may not be as familiar with the nature of the work as those who have been long in the service.

Quarterly Practices.—Several instructors remarked upon the need, in their opinion, of holding the practices of the trained men drawn from the mines more often than quarterly. At only one place (New Tredegar), however, did we meet with an instance where the brigades attended at the station more frequently than quarterly and at that station they assemble six times a year. It goes without saying that such a course is advantageous. We desire to draw the attention of the Management Committees of rescue stations to the advisability of considering whether more frequent meetings of the trained men employed at the mines shall not be arranged.

There is no necessity to advocate any change in the Regulations on this point. Neither General Regulation 140 (d) (ii) nor the Scheme of Training and Practice under the Amended General Regulations of May, 1914, make any hard-and-fast requirement for quarterly practices; they state that there shall be at least one practice every quarter with breathing apparatus. Nor do we think it desirable to recommend an increase in this compulsory minimum yearly number; for we believe, with apparatus of that simplicity of construction and reliability of action which should be the aim of all future improvement, four practices per annum would be in many cases enough to maintain efficiency.

Underground Practices.—By the present Regulations, at least two of the four practices to be undertaken in any year as a minimum by a trained colliery brigade must take place at the mine. In some areas this rule is conscientiously followed in others no practices are carried out at the mines.

It is a striking fact that just where underground practices are regularly taken the instructors are most convinced of their desirability. Some of those we sternly holding the opposite view base their objection upon the supposition that the men, knowing the air to be fresh, will not “play straight,” and perform their task with their mouthpieces off or their mouthpieces out. The temptation undoubtedly exists; but an alert instructor very soon detects a man who has fallen to it. If a suspected person is made suddenly to answer to his name and voice will at once show whether his mouthpiece is in place or not. Experience proves, as a matter of fact, that cheating of this kind is exceptional.

Advantage of Underground Practices.—Many persons, we find, are still of the opinion that work in a gallery is a severer test on the apparatus than work
the mine, and they express a preference for gallery practices on that ground. We cannot too frequently insist that, from the standpoint of respiratory exertion, walking along a flat road, and especially climbing an incline, is much more severe than the kind of labour usually performed in the restricted space of a station gallery, and therefore a more stringent test of the capability of the apparatus and its wearer. An apparatus may behave satisfactorily in a gallery but break down in the pit. No more marked example of this could be quoted than that which occurred at the Duchi Colliery, Pontycymer, on March 2nd, 1917. The colliery brigade equipped with Draeger apparatus fitted with purifiers that had been improperly refilled, but nevertheless in the condition in which they had been regularly used at the station, attempted to climb a rough old road, leading to unventilated workings, and rising at about 1 in 5. The distance was short and the pace at which the men travelled was very slow; yet the apparatus failed dismally, one member of the brigade and the instructor losing their lives and the others barely escaping. (See p. 22.)

Underground Practices strongly recommended.—We are strongly of the opinion that underground practices are essential, and that the rule which relates to them should be strictly observed.

Underground Practices for Resident Brigades.—A decided weakness of the resident brigade system is that there is no compulsion for such a brigade to undergo any underground practices at all. The memorandum attached to the Official Scheme of Training* draws attention to the advisability of practices in the mines, the words being as follows:—

"It seems very desirable that some of the periodical practices (after training) of the central rescue-corps should take place at the mines, so as to familiarise the corps with actual mining conditions. This is required by the earlier regulations in the case of rescue-brigades, and would seem equally important in respect of the central corps."

Compulsory Underground Practices for Resident Corps recommended.—We go a step further. We consider that it should be made compulsory for resident corps to undergo at least six underground practices with breathing apparatus per year; that these practices should, as far as possible, take place at different mines; and that on each of these occasions the corps should be accompanied by trained men connected with the mine, who also should wear breathing apparatus. To facilitate these practices, it should be permissible for the instructor to divide a corps into two or three squads, should be desire, and for the squads to take underground drill on different days. The purpose of these drills at the mines is to make the members aware of the behaviour of the apparatus under conditions (e.g., climbing inclines) which involve hard respiratory exertion, to accustom them to travelling underground roads of all kinds with apparatus, to familiarise them with at least some part of the workings in their area, and to bring them into frequent contact with the trained men of the mines. Arrangements should be made that one-half of the practices of the trained men employed at the mines take place underground.

Resident Brigade System: Grouping of Men from the Mines.—The resident brigade system has not yet been put to the proof of actual service in first-magnitude accidents. It is therefore impossible to say how it will compare with the older system in such a case. Experience at the Norton Hill and Podmore Hall collieries, however, makes it certain that recovery after a large-scale explosion may call for the services of rescue brigades without pause for a protracted period, and, having regard to the brevity of a shift with breathing apparatus, the doubt arises as to whether the resident brigade system would in these circumstances provide a sufficiency of reserve teams. Evidently it would be necessary to fall back upon squads formed from trained men drawn from other mines, and such an eventuality should, we think, be borne in mind during the training and subsequent practising of these men. We suggest that, except where the number at a mine be sufficient to form in themselves an efficient brigade, the trained men be grouped together, so far as

* Mines and Quarries, Form 72, p. 2.
is practicable, into definite brigades, each of not less than five members, who train and practise together. A brigade so constituted would be vastly more reliable at a time of stress than one built up, on the spur of the moment, of men who may be strangers to each other.

The Staffing of Central Stations.—We cannot view without misgiving the position of a central station at which the instructor is without a single assistant as happens in some instances at present. Such a station must on occasion be let without an attendant. We think that two competent persons should be the minimum number employed at even the smallest central station. In some cases two persons are insufficient to cope with the work of a station serving a large district, and to make provision for this we consider that the number of competent persons at the stations should be in accordance with the importance of the area served by it. Under the original or non-resident scheme that number should not less than two when the number of trained colliery brigades is less than fifty, not less than three when the number of brigades lies between fifty and one hundred, and not less than four when the brigades exceed one hundred in number.

For the resident corps system the number of competent persons, in addition to the permanent corps, should be not less than two in any case, and not less than three if the number of underground employees at all the mines served by the station exceeds 15,000.

Qualifications of a Station Officer.—By the term "competent person" we wish to be understood an officer capable of taking full charge of the station, conversant with the use and adjustment of the appliances, able to give instruction in the subjects prescribed in training men in rescue work, and qualified to drive the motor car at the station. These persons should either reside at or adjoining the station or have their houses in telephonic communication therewith.

Mr. Stevenson's Scheme of Station Organisations.—Mr. David Stevenson, of Cowdenbeath Rescue Station, submitted to the Committee a scheme of organisation which possesses several advantages. He proposes that there shall be a permanent corps attached to the station, and that the members shall live at the station or in its vicinity. In place, however, of having the corps continuously employed at the station, Mr. Stevenson considers that the men should be engaged at one or more of the neighbouring mines. They would then be kept in daily touch with practical mining and in hard physical condition.

We suggest that regulations be drafted to allow of this system being adopted should it be preferred to either of the present systems. The regulations might require, inter alia, that:

(a) The central corps (apart from the station officers) should consist of not less than fifteen men;
(b) These men should be distributed equally over the three working shifts;
(c) They should not be employed at mines distant more than two miles from the rescue station;
(d) The central corps should live at the station or in its vicinity, and the houses (if apart from the station) should be connected to the station telephones or electric alarms;
(e) After completing their training, the central corps should undergo, at least monthly, practices with apparatus, of which at least two per annum should be underground;
(f) One or more persons employed at each mine within ten miles of the station should be selected for training on the scale set forth in General Regulations, 19th May, 1914, 1 (b);
(g) These persons from the mines should, after training, undergo at least six practices with apparatus per annum, of which half the number shall be underground and the remainder in a hot or irresistable atmosphere at the station;
(h) In the case of a mine at which one or more of the central corps are engaged, the minimum number of additional men to be selected for training should be the number stipulated by the above-named General Regulations less the number of the central corps there employed;
(c) There should be at least two station officers (apart from the central corps) qualified to take full control of the station and appliances. If the total number of underground employees at the mines served by the station exceeds 15,000, there should be at least three such officers. At least one of these officers should reside constantly at the station.

Instruction in Plan Reading and Gas Detection.—A portion of General Regulation 140 (d) reads as follows: “The members of the brigade shall have received instruction in the reading of mine plans, in the use and construction of breathing apparatus, in the properties and detection of poisonous or inflammable gases, and in the various appliances used in connection with mine rescue and recovery work.”

With some exceptions, rescue station instructors (either on the plea of lack of time or that it was carried out at the mines) have neglected to observe this regulation. By subjecting to regulation the number of station officers competent to undertake this instruction, as we have proposed, the chief difficulty in the way of its being given, namely, insufficiency of staff, will be removed.

Properly to deal with the subjects set forth in the regulation quoted, requires the instructor to devote an hour to those subjects at each of the 13 meetings needed for training, in addition to the practice with apparatus.

Gas-testing Apparatus.—Apparatus specially designed for teaching gas-detection can be obtained in many forms. Most readers of this Report will already be familiar with several of these apparatus, and a detailed description need not, therefore, be given. Clowes’ chamber (described in Clowes and Redwood’s book on “The Detection of Inflammable Gas and Vapour’’); Winstanley’s (Trans. I.M.E., XXXVIII, 235); and the H. W. C. No. 2 (Baird and Tatlock, Glasgow) of the simple kinds, and the Oldham chamber (Messrs. Oldham and Son, Denton, Manchester) of the more elaborate types are the best known.

The Airtight Chamber.—Another method (with many advantages) of studying the detection and properties of mine gases is to use an airtight chamber fitted with observation windows and an airtight door. Such a chamber can be made large enough to accommodate several persons, who can thus observe the influence (if any) of a gas on themselves. A chamber of this kind can be made sufficiently gastight to keep an atmosphere for several days. An inlet pipe is required to bring in gas whose volume can be measured by a meter on the pipe. The chamber is also serviceable in running tests in hot moist air. A Martin bicycle ergometer at one and the same time offers something for the subject to do and measures the work he does, while a steam pipe, with a cock that can be opened in the chamber, provides the means of heating the air and changing its hygrometric state.

Carbon Monoxide.—In the hands of a competent teacher any of the appliances named is perfectly satisfactory in demonstrating in a practical manner the properties of firedamp, blackdamp, and carbon monoxide. Men possessing the fireman’s or shotfirer’s certificate could be excused that part of the instruction which relates to firedamp. The most convenient way of demonstrating the influence of carbon monoxide—to rescue men the most important of the noxious gases—is to use lighting gas for the purpose, a bird being placed in a cage into which is passed air containing the gas in known proportion. The town gas engineer will generally inform a responsible applicant of the composition of the gas. The gas apparatus is adjusted in accordance with the percentage of CO in the lighting gas used. For example, if that gas should contain 12 per cent. of CO, $\frac{1}{12}$ per cent. of the gas will be required to furnish a $\frac{1}{3}$ per cent. supply of carbon monoxide. In the small proportions here being used the other constituents of lighting gas have no appreciable influence on an animal, and can be regarded as inert.

The men should be taught to observe the first indications, on the part of the animal, of gas poisoning. They should measure the time between the moment of insertion into the gas and this preliminary indication for different percentages, and particularly for proportions between $\frac{1}{4}$ per cent. and 1 per cent. They should also time the moment of collapse, and the period required for the animal to recover, first in fresh air and then in oxygen.

Blackdamp.—Blackdamp (nitrogen plus a relatively small amount of carbon dioxide) can readily be made by burning a methylated spirit flame or gas flame in a closed box, such as the Clowes’ chamber. The composition of the blackdamp thus produced resembles that usually found in British coal mines. The instructor should show how the blackdamp percentage (or, conversely, the oxygen percentage) can be ascertained both by Dr. Haldane’s tube-and-taper* test (Trans. I.M.E. XII, 455) and Dr. Briggs’ oxymeter safety lamp† (Trans. I.M.E., LI, 169). He should assist the men to determine by experiment the proportion of oxygen in the air at the extinction points of an ordinary light (candle or spout lamp), Marsden safety lamp, A.H.G. safety lamp and acetylene flame. He should call attention to the reduced luminosity of flames in the presence of blackdamp, and to the curious phenomena exhibited by the acetylene flame when nearing the point of extinction. During these tests on lamps, it is instructive to have a bird in the chamber at the same time in order to show how insensitive a bird or a man is even to large percentages of firedamp or blackdamp.

With the large airtight chamber these experiments can be usefully developed by letting the men see and feel the effects, or absence of effects, while breathing air contaminated by various gases, both during rest and during work; and the efficiency of rescue apparatus as a protection against these gases can also be demonstrated.

Supply of Compressed Gas.—It may not be known to all that CO₂, nitrogen, and pit firedamp can be obtained in the compressed form in steel cylinders. The two former gases, which are supplied through the larger chemical dealers, allow of blackdamp being made quickly and in large quantities. The latter is sold by Messrs. Insole’s Limited, Porth, South Wales, and is to be preferred to lighting gas in instructing men in firedamp detection.

If time permits, the practical course in the properties and detection of mine gases, which has been sketched out above, can be supplemented by classroom instruction on the subject; but lectures without thorough practical demonstration are of little use to members of rescue teams. In several districts advantage could be taken of local mining schools in giving instruction in gas detection, arrangement being made with the Educational Authorities to take the brigade members for a special practical course along the lines we indicate. Much is to be gained by co-operation between the rescue stations and existing educational machinery.

Uniform Code of Ventilation Signs.—In order to systematise instruction in plan reading, we think it advisable to adopt a uniform code of conventional signs for ventilation plans. Such a code will be found in Appendix I. (p. 47). Our suggestion is that the code should be incorporated in the Rules relating to Rescue Operations, which are framed in compliance with General Regulation 145. This would lead to the code of signs being followed by surveyors in preparing the tracings under General Regulation 141 (b). It would be advantageous if that code were used in draughting all ventilation plans.

If the code is examined it will be seen to include signs for doors, stoppings, air crossings, regulators, and telephone stations, these being specifically mentioned in General Regulation 141 (b). In addition, a sign is given for the ambulance stations referred to by General Regulations 147, and another for a stopping put in with the object of sealing off a fire. As the Coal Mines Act distinguishes between explosion-proof stoppings and air crossings and others, we think that it is logical to provide for the same distinction in the code of signs.

Instruction in Plan Reading.—In teaching a man how to read a ventilation plan, copies of simplified plans, such as those used in the examinations for mine managers’ certificates, are valuable. At one rescue station a number of these plans have been printed, and large wall diagrams of the same plans prepared. The forms are blank so far as ventilation signs are concerned, but the latter are complete in this respect, and telephones and ambulance boxes are also shown in the manner exemplified by Fig. 36. When a team is receiving instruction in plan reading every man has a blank plan before him; the instructor deals with the plan with...
FIG. 36: SECTIONAL VENTILATION PLAN PREPARED FOR RESCUE BRIGADE.
the assistance of the wall diagram, and the men mark their own copies to correspond with that diagram. A few questions addressed to the men, such as: "Which is the best way to get from this point to that?" "What would happen if such and such a stopping or door were blown out?" "What is the reason for putting a regulator here?" raise interest and drive the lesson home. After spending some time in this way, actual ventilation plans of neighbouring pits should be examined.

Ventilation Tracings to be sent to the Rescue Stations.—It would facilitate teaching if mine managers made a rule to forward to the rescue station the tracings made in compliance with General Regulations 142 (b) as soon as they are superseded by others. The brigades could then familiarise themselves with the actual thing.

Instruction in Construction of Apparatus, &c.—Instruction in "the construction, use, repair and maintenance of the type or types of breathing apparatus provided for the corps, and of smoke helmets" is required to be given to members of rescue brigades, and should also be obligatory for the teams attached to the station in Mr. Stevenson's scheme, if that scheme is officially sanctioned. Obviously the training of station corps in the appliances they have to use cannot be made too thorough. They should constantly practise assembling the parts of apparatus, and should undertake cleaning and recharging. In particular should they know how to test apparatus and how to keep it in repair. There is no better way of learning the idiosyncrasies of any mechanical device than to be compelled to keep it in repair and adjustment. An excellent system is in vogue at the Northumberland and Durham Stations of encouraging suggestions and improvements from the corps, and of recording the best proposals in the books of the station. It is worthy of being adopted elsewhere.

In the case of colliery brigades the Regulations do not specify so precisely and fully the nature of the training in the subjects under discussion as they do with resident corps. They merely require that mine brigades shall receive instruction "in the subjects mentioned in Regulation 140 (d) (3)." This Regulation refers to "the use and construction of breathing apparatus," but not to the repair and maintenance of the apparatus. Nevertheless colliery brigades should be made familiar with the appliances they employ. At the Brigham Station, to ascertain if a man knows his apparatus, he is confronted with a dismantled apparatus, the parts of which are purposely mixed in disorder, and he is asked to put them together. This is an excellent test.

Instruction in Testing of Apparatus.—The captain and vice-captain (at least) of a colliery brigade and every member of a permanent corps should be able to test rescue apparatus for leakage and for oxygen supply, and we think that instructors should insist on the leader of a brigade himself performing these tests for all the apparatus of his squad before the men put them on. The leader would then not be at a loss if called upon, in the case of an actual emergency, to carry out Rule 9 of the code in Appendix I.

Instruction in Appliances for Rescue and Recovery.—According to the Regulations all members of rescue brigades shall also receive instruction in "the various appliances used in connection with mine rescue and recovery work." These appliances include the smoke helmet, the various forms of reviving or resuscitating apparatus and the portable telephone. Air samples are often useful in recovery work, and we think the teams should be taught how to take these samples in irrespirable atmospheres. At the Northumberland and Durham stations instruction is given in the use of light fire pumps specially designed for underground service—a procedure which could beneficially be introduced elsewhere.

We intend to deal in detail with both reviving apparatus and smoke helmets in a subsequent report. Just now we are concerned more with the nature of the training with these devices than with their construction. It is however necessary to state that, so far as revivers are concerned, our preference at present leans more towards the simplest type rather than towards the more elaborate. We therefore think that special attention should be directed to training with the simple form. We also consider that every member of a team should be competent to apply Schafer's method of artificial respiration either with or without an apparatus for breathing oxygen.
Although the Official Scheme of Training* stipulates that training in “the establishment of telephonic communication” shall be given, we have found for rescue stations which possess the necessary appliances. Yet this operation is of great practical value. Ready means of communication between a working party and the pit bottom or the surface expedites recovery operations, inspires confidence in the men, and makes for safety. Instruction should be given in the assumption that the brigade, wearing breathing apparatus, has been required to push forward in advance of fresh air to prepare the line of communication. The minimum equipment consists of two portable telephone sets (the military fig. pattern is probably the best) and a drum holding a length of light flexible twin core cable, slung from the shoulders of one of the men. At least 500 yards of the cable should be kept at the station. A shorter length may also be provided for practice purposes. One of the leading men unwinds the cable, and the others take it out of the way of traffic, and if possible to the timber, by means of staples. Practice is needed to conduct this operation speedily and without confusion, keeping the men well together. The best place to carry out the work is in the pit, as certain of the underground practices should be devoted to it. A convenient line is selected as fresh air base, and here one of the instruments is placed; the other is carried inbye. Both instruments are fitted with buzzers, so that either end can be “ring up” the other end.

Uniform Signalling Code advocated.—Spoken messages from the base to the working party can, of course, be transmitted; but all communications from the party to the base should, as a general rule, be by signal. It is sometimes possible to make out what a man says when speaking with his mouthpiece in, even through the telephone, but the message is indistinct at the best. Signalling with a bell or buzzer is more definite, usually more expeditions, and obviates the temptation of removing the mouthpiece in order to talk clearly. We recommend the general adoption of the code of signals set forth in Appendix I. All signals received should be repeated to the transmitter.

Signalling while laying the Cable.—At the Newcastle, Wath, and Mansfield Stations an improvement has been effected by placing two insulated sliprings at one end of the shaft of the cable drum, the inner ends of the cable wires being respectively connected to the rings. Fixed brushes rest on the rings. The brushes are connected to terminals on the frame supporting the drum, and the whole telephone is, in turn, connected to these terminals. This arrangement makes a connection between the telephones complete at all times, and they can be used while the cable is being coiled or uncoiled.

A slightly simpler arrangement for the same purpose is adopted at the Edinburg Station. The reel shaft is in three parts, namely, a stout wooden centre boss, with steel trunnions fixed into it at either side. The wood thus insulates the trunnions from each other. The trunnions are respectively connected to the inner ends of the cable, and the telephone to fixed terminals inside the box in which the shaft is carried, these terminals being in turn connected to the bearings of the reel. This arrangement does away with brushes.

Signalling between Members of a Brigade.—The signalling code of Appendix has been devised to suit signals transmitted by other means as well as by telephones, buzzers or electric bells. To make it always readily possible for members of a rescue team to signal to each other, we think it highly advisable that every member of the rescue brigade should carry a cycle horn, or some equivalent contrivance, for transmitting definite and distinct signals, and that he should be thoroughly practised in making and taking signals according to a prescribed code. The rules, to which are now about to refer, were drafted on the assumption that a horn or equivalent forms an essential item of equipment of a brigade member.

Codification of Rules.—As long ago as 1891, in giving evidence before the Royal Commission on Coal Dust Explosions,† Sir William Garforth suggested the drafting of rules to assist mine managers in the event of an explosion; and

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* Mines and Quarries, Form 72, p. 1.
1897 he drew up a code,* which has served as the model for those now in vogue in most districts maintaining rescue stations. General Regulation 145 requires rules of this kind to be adopted at every coal mine, and stipulates that the members of the brigades be instructed in them. In spite of a certain similarity between the various sets of rules, considerable differences exist in scope, arrangement and extent of detail. We consider diversity in this instance to be a weakness, and recommend the adoption by all mines of a single code such as that printed as an appendix to this Report. Incorporated in the proposed Rules are several suggestions to be found elsewhere in the Report. Our endeavour has been to make the code suitable for both the resident and non-resident brigade systems. In drafting it we have been assisted by the existing rules relating to rescue operations, which were sent to us from most of the rescue stations.

Nothing is intended to prevent station managers or superintendents adding to the general code such other rules (particularly those of a disciplinary nature) as are called for by their particular circumstances.

Dividing the Rules under headings, as has been done in Appendix I., facilitates both reference and teaching. It will be observed that the rules relating specifically to the ordinary members of brigades are few, simple, and easily learned. Both the captain and vice-captain of a colliery team should be familiar with the rules set forth under the head of "Captain." We also think that members of a resident corps should know the captain's rules, as in a protracted piece of recovery work any member may be required to lead a team consisting of trained men from the mines.

Additional Instruction of Captains.—The course which has been followed for several years at Birmingham University of providing special instruction for instructors and captains of brigades, is excellent. Similar schemes, either in connection with teaching institutions or with the rescue stations themselves, could not fail to be beneficial. While preferring to leave the matter on the voluntary basis, we think that "intensive" courses for captains, including gas detection, plan-reading, ambulance, and the assemblage, recharging, testing and repair of apparatus should be established at many centres. Mr. G. L. Brown has made the good suggestion that the captains should be encouraged to form volunteer station squads of four or five, and that each squad should attend the rescue station frequently to assist the regular staff. Many, we feel sure, would join such squads, and by continual handling of the apparatus improve their knowledge and efficiency.

Provision of Red Cross Rooms at Mines.—A measure which we think should be made compulsory is the provision, at every mine at which trained rescue men are required to be maintained, of a room set apart for rescue and aid purposes. This room, situated conveniently near the shaft or outlet of the mine, should be distinguished by a large Red Cross painted on the door. It should be dry and well lighted, have a plentiful supply of drinking and washing water, a strong table, and lockers, drawers and shelves for storing the articles named below. It should be placed in the definite charge of a person, appointed in writing by the Manager, who holds an approved ambulance certificate, and who is made responsible for the proper maintenance of the room, fittings and equipment.

Within this room there should be kept the various articles for rescue and ambulance purposes specified by General Regulations, viz.:—

(a) The birds or mice, electric hand-lamps, safety lamps, oxygen reviving apparatus, ambulance box and stretcher in accordance with General Regulations 142 (c) and 147, and Amended General Regulation 1 (d), (19th May, 1914);

(b) The ventilation tracings (General Regulations 142 (b) and Amended General Regulation 1 (c)) in a suitable form for use in rescue operations;

(c) The breathing apparatus or smoke helmets in accordance with General Regulation 142 (a) and Amended General Regulation 1 (d).

To these there should be added:

(d) A list of the names and addresses of the trained men at the mine station, the shifts on which they are usually employed. The list is preferably ruled up like a register or time sheet so that each man's attendance at quarterly practices can be seen at a glance;

(e) A placard stating the telephone numbers of (1) the central station, (2) the Divisional Inspector of Mines, (3) the pits in the district associated with the central station, (4) the local doctors, (5) the police station.

The captains of brigades under the old system, and all the trained men at the pit under the new system, should be made thoroughly familiar with the position of every article in the Red Cross room.

Appointment of Quartermasters at Mines.—At collieries in the Stoke-on-Trent district, as the outcome of extensive experience in recovery work with respirators, they have adopted the plan of appointing quartermasters, whose duties are to see to the refreshment and general comfort of rescue teams. Although commended by Garforth*—who saw its utility after the Altofts explosion, 1889—this course has not received the attention it deserves. Yet it is evident the brigades cannot be expected to keep fit during protracted operations without proper organisation for commissariat, bathing and resting, and for changing, drying and disinfecting clothing. One person could conveniently combine the duties of quartermaster and caretaker of the Red Cross room.

Competitions between Brigades.—The system in vogue in most mining districts of forming mine ambulance teams and of holding annual competitions between them has been productive of much good. We should like to see a similar system developed for rescue teams. Competitive meetings between such teams are frequently held in the United States, and inspire a good deal of interest.

We see no reason to prevent each district setting up an organisation (which can be a development of the existing ambulance organisation, or connected with it) if the purpose of holding an annual competitive meeting at the local rescue station is decide the award of a challenge cup. Once the district associations were established, it would not be difficult to proceed another step and arrange for an annual event at which the cup holders would meet and compete for a national shield. There we consider, no better way than this of stimulating interest in the subject of rescue training among miners, of encouraging enlistment for the brigades, and maintaining the zest and efficiency of the members.

Annual Conference of Rescue Station Instructors suggested.—With the object of discussing matters of common interest, Sir John Cadman has made a practice for some time of convening meetings at the University of Birmingham at which the instructors in charge of rescue stations in that area. We suggest that the system be extended to embrace the country as a whole, the conferences to be held annually at towns in the vicinity of rescue stations. The meetings could conveniently be made to coincide with those of the national competition dealt with in the last paragraph.

Without making special provision for such annual conferences, to which every central rescue station should send at least one delegate, instructors—widely scattered as they are—will find difficulty in keeping in touch with all developments of their rapidly evolving subject. By discussing papers, exchanging experiences, and inspecting other rescue stations than their own, a great deal of benefit will accrue to all. The meetings should be open to mine officials and to the captains and members of rescue brigades.

Suggested inclusion of certain mines under the Rescue Regulations.—At present, mines other than coal mines are exempt from the provisions relating to rescue work, in consideration of their immunity from large-scale explosions. Owing to the chief spheres of utility of breathing apparatus, however, lies in dealing with underground fires, and on several occasions it has proved its value at such occasion as

* Ibid.
Very few mines can be considered free from all risk of fire, and at least one exempted class, namely the Scottish Oilshale Mines, appears particularly prone to this kind of accident. On two occasions in the last two years shale mines have called for the services of rescue stations, and on both occasions self-contained apparatus came into use as well as smoke helmets.

We consider that it would be advisable to include shale mines under the Regulations respecting rescue operations.

Metalliferous mines in this country are not required to make any provision for rescue work, yet on two occasions the Brigham (Cumberland) Station has been called upon for assistance at iron-ore mines. On the last occasion a colliery brigade had to be requisitioned, and, by its aid, the life of one man, gassed by carbon monoxide, was saved. We think the question of applying the rescue regulations to mines or classes of mines under the Metalliferous Mines Regulation Act should be taken into consideration when any new legislation relating to these mines is being introduced.

W. WALKER,
Chairman of Committee.
J. S. HALDANE.
HY. BRIGGS.

February 14, 1918.

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APPENDIX I.

SUGGESTED UNIFORM CODE OF RULES FOR THE CONDUCT AND GUIDANCE OF PERSONS EMPLOYED IN RESCUE WORK.

MANAGER OR PRINCIPAL OFFICIAL FOR THE TIME BEING AT THE SURFACE OF THE MINE.

1. On receiving information of any occurrence likely to require the service of rescue apparatus, the following steps shall be taken by the Manager, or, in his absence, by the principal official present at the surface:

   (a) Telephone to the Central Rescue Station. Inform the Instructor of the character of the occurrence. State whether assistance will be needed from rescue brigades other than the permanent station corps or the brigades attached to the mine;
   (b) Summon the trained men attached to the mine;
   (c) Telephone for medical assistance;
   (d) Telephone to the Inspector of Mines;
   (e) If necessary, communicate with the police station.

2. No person shall be allowed to enter the mine or the part of the mine which is unsafe for the purpose of engaging in rescue operations unless authorised by the Manager, or, in his absence, by the principal official of the mine present at the surface; and, during the progress of such operations, a person or persons shall be stationed at the entrance of the mine, and required to keep a written record of all persons entering and leaving the mine. Only men trained with the apparatus shall be permitted to enter the mine for the purpose of using rescue apparatus.

3. Prior to sending a brigade underground clear instructions shall be given to the leader of the brigade as to where it shall go and what it shall attempt.
Unless the leader is personally thoroughly familiar with the roadways in question the route shall be marked on a tracing, which the leader shall take with him to the mine.

4. A qualified medical man shall be in attendance at the mine wherever rescue parties are at work, unless in the opinion of the Manager and Inspector of Mines that course is unnecessary.

The doctor, when present, shall examine every man engaged in rescue work before permitting him to go underground for a second spell of that work.

5. As soon as possible a base or bases shall be established in fresh air, but near to the irrespirable zone or zones as safety permits. Each such base shall, if possible, be connected by telephone to the surface or to the shaft bottom. Wherever men are at work beyond the base there shall be stationed at the base at least the following: (a) Two men, of which at least one should understand rescue appliances and first aid; (b) A spare brigade with rescue apparatus and ready immediate service; (c) One or more oxygen revivers, stretchers and birds.

**CAPTAIN OR LEADER OF A RESCUE BRIGADE.**

6. The leader shall not permit the brigade to go underground until he received clear instructions from the Manager or from the person acting as Manager's behalf; and, unless the leader knows the route thoroughly, he shall take underground a plan on which the route is clearly marked.

7. The leader shall not engage in manual work. He shall give his attention solely to directing the brigade and to maintaining its safety. He shall examine roof and supports during the outward journey, and, if there is any likelihood of a fall he shall not proceed until the brigade has made the place secure. He shall take the brigade through any passage less than two feet high and three feet wide except in a case of urgent necessity.

8. When the atmosphere is clear, the leader shall, when passing the junction of two or more roads, clearly indicate the route by means of arrow marks in the road. When the atmosphere is thick with smoke the leader shall see that a life-line is led in from fresh air, and shall not allow any member of the brigade to move or reach that line; or, if that course is impracticable, he shall not proceed until every road branching from the route is fenced across the opening.

9. Before proceeding underground the leader shall test, or witness the testing, of every rescue apparatus of the brigade. He shall check the equipment of his party, and, immediately before entering irrespirable air, make sure that every apparatus is working properly.

10. When using rescue apparatus the leader (who shall carry a watch) shall read the pressure of the compressed oxygen every 20 minutes, or thereabouts, and shall commence the return journey in ample time. In travelling he shall adapt the rate to that of the slowest member.

**MEMBERS OF RESCUE BRIGADES.**

11. Members of brigades shall, in general, use the prescribed signals in communicating to one another.

12. In travelling with rescue apparatus, each member of the brigade shall the place given him when numbering off. If the pace is too quick, or if distress is felt for any reason, the member shall at once sound the distress signal.

13. No person shall commence a second or subsequent spell of work in the tunnel without being examined and passed by a doctor, if present, or by the rescue instructor or other competent person if the doctor be not present.
### CODE OF SIGNALS.
*(To be used when working in poisonous air.)*

<table>
<thead>
<tr>
<th>Electric Signalling</th>
<th>Signalling between Members of a Brigade</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Distress&quot; or &quot;Help Wanted.&quot;</td>
<td>&quot;Distress&quot; or &quot;Help Wanted.&quot;</td>
<td>ONE prolonged ring, or a prolonged succession of hoots.</td>
</tr>
<tr>
<td>(IF NO ANSWER is given to a call, &quot;Distress&quot; is to be understood.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Not understood&quot; or &quot;Repeat the Message.&quot;</td>
<td>Halt</td>
<td>ONE sharp ring or ONE hoot.</td>
</tr>
<tr>
<td>&quot;No&quot;</td>
<td>Retire</td>
<td>TWO sharp rings or TWO hoots.</td>
</tr>
<tr>
<td>&quot;Yes&quot; or &quot;All right&quot; or &quot;All's well.&quot;</td>
<td>Advance</td>
<td>THREE sharp rings or THREE hoots.</td>
</tr>
<tr>
<td>To &quot;ring up.&quot; To &quot;ring off.&quot;</td>
<td>To call attention</td>
<td>FOUR sharp rings or FOUR hoots.</td>
</tr>
</tbody>
</table>

### CODE OF VENTILATION SIGNS.

- **Brick, Stone, or Concrete Stoppings, explosion proof** *(General Regulation 91)*
- **Brick, Stone, or Concrete Stoppings other than the above**
- **Fire Dams or Seals**
- **Doors**
- **Regulator**
- **Air Crossings, explosion proof** *(Section 42 (3), C.M.A., 1911)*
- **Air Crossings other than the above**
- **Telephones**
- **Underground Ambulance Station** *(in red)*

**Direction of Air Current**
- Intake Airways—Blue.
- Return Airways—Red.
APPENDIX II.

APPARATUS FOR THE ESTIMATION OF NITROGEN IN COMPRESSED OXYGEN.

1. Graham's Apparatus.

The oxygen is absorbed from a measured quantity of the sample by means of a concentrated solution of sodium pyrogallate and the residual nitrogen measured. A determination of the nitrogen content of an oxygen cylinder sample may be made in a few minutes and with no greater error than 0.1 per cent. The apparatus consists essentially of a measuring vessel $A$ (Fig. 37) of 10cc. capacity, an oxygen absorption vessel, $B$, and a caustic soda solution trap, $D E$, with a mercury reservoir $F$. The burette $A$ is filled with oxygen to the 10cc. mark, is just above the 3-way cock $T_2$, and the residue after absorption is read by means of the graduations on the narrow portion below the upper 3-way cock, $T_1$. The finest division represents 0.2 per cent of the volume of the sample. The right hand arm of the upper tap $T_1$, just above the latter, is enlarged into a small

![Fig. 37.—Graham's Oxygen Analysis Apparatus.](image-url)
This arm is connected to the pipette BC (containing a concentrated alkaline solution of pyrogallic acid) by a short piece of india-rubber pressure tubing. B is fitted with glass tubing, so as to offer the largest surface of pyro solution to the gas when the latter is passed from A into B. C has a capacity of about 150 cc., and is thus able to hold a large volume of the absorbent with consequent elimination of the necessity for frequent changing of the latter. D E contains concentrated caustic soda solution, and acts as a seal between the air and the pyro solution. E is held by a spring clip, and can be raised or lowered so as to adjust the level of the pyro solution to the graduation mark b.

The right-hand arm of the tap T₂ connects to a mercury reservoir F, and the left-hand arm to the oxygen inlet tube. The latter is fitted with a T-piece G, the leg of which almost reaches to the bottom of the cylinder of water H, and acts as a blow-off valve when T₂ is closed. The left-hand arm of the upper tap T₁ is connected to the exit tube I, which only just dips below the surface of the water in H.

The object of the small bulb a, which contains nitrogen before and after the analysis of the sample, is to facilitate the absorption of oxygen, especially towards the end of the operation. Before starting a series of analyses, the bulb a must be filled with nitrogen at atmospheric pressure. This is done by first turning T₁ to connect A with the exit tube and air (the end of I being raised slightly above the surface of water in H), and then drawing a little air into the burette by lowering the reservoir F. Now turning T₁ to connect A with B, the gas in A is passed to and fro between A and B by raising and lowering the reservoir F. In every case the latter is raised sufficiently high to bring the mercury to the top of a, so that practically all the gas is driven over into B. When returning the gas to the burette care must be taken not to lower the reservoir too far or the pyro is sucked above the mark b. About seven passages of the gas, to-and-fro, are usually sufficient to clear it of oxygen and CO₂. The volume of the residual gas is measured after bringing the pyro solution to the mark b. This is best done with the aid of the rack R, the mercury reservoir being hooked to the latter. The gas should then be passed another three or four times into B, and a second reading taken. If the absorption has been complete these two readings will be identical. T₁ is then turned to connect A with I. The bulb a now contains only nitrogen at atmospheric pressure, the pyro solution standing at the mark b.

The end of I is raised just out of the water in H, and the mercury withdrawn from the burette until its surface stands between the tap T₂ and the 10 cc. graduation. T₂ is turned to connect with the inlet tube K, which is now joined up to the oxygen cylinder through a reducing valve and a length of rubber tubing. The oxygen is turned on and allowed to flow through the burette and out of the exit tube for about one minute, at the rate of 600 or 700 cubic centimetres per minute. While the oxygen sample is passing through the burette the mercury reservoir, suspended from the bottom hook on the ratchet, is raised to such a position, that, on connecting to the burette, the mercury will flow into the latter up to the 10 cc. mark. This position is easily found beforehand, and a line, to indicate it, drawn on the wooden stand.

After the passage of 600-700 cc. of sample through the burette, the cylinder is turned off and T₂ turned to connect A with the reservoir; the mercury then flows into the burette up to the 10 cc. mark, the small quantity of oxygen displaced bubbling out of I. (No correction need be applied should the mercury be 0-01 cc. above or below the mark.) T₁ is turned to connect A with the pyro, and the sample in A is passed to and fro between A and B ten or twelve times, the pyro brought to the mark b, and the volume of residual gas in A read off. Three or four additional passages to and fro and a second reading will show whether the absorption of oxygen has been complete—as should be the case. This reading gives the percentage of nitrogen present in the sample.

To analyse a second sample, T₁ is turned to connect to the exit tube I (the end of which is raised just above the surface of the water), and the reservoir F is lowered until the mercury can be seen to be just above the tap T. The latter is then turned to connect with the inlet tube, and a sample taken from the cylinder and analysed as before. The time taken in getting the sample and doing the analysis should not exceed six or seven minutes.
Particulars of a slight modification of the apparatus suitable for analysing samples of volatilised liquid air, together with instructions on cleaning the apparatus, are given in the pamphlet issued by the makers, Messrs. Siebe, Gorman & Co., Ltd., Westminster Bridge Road, London, S.E.


The apparatus is illustrated in Fig. 38. It is carried on a wooden stand (shown by dotted lines) which is firmly screwed down to a table or bench. There should be a good light behind the apparatus.

![Fig. 38. Briggs' Oxygen Analysis Apparatus.](image)

The portion J, K, L, M is an absorption arrangement similar to that adopted by Dr. Haldane’s gas analysis apparatus, or in Mr. Graham’s apparatus just described.

A is the measuring burette. It has a single-way stop-cock B (the only glass part on the apparatus), and it is open at the bottom end. A A-shaped piece C, has been ground out of the bottom edge of the burette, thus providing a definite plu...
at which oxygen, blowing down the burette, must discharge into the water which surrounds it. The upper end of the burette is narrowed, and graduated in percentages and decimals.

The burette is supported within the jacket tube O, which is connected by rubber tubing to the leveller P. The latter is held in an adjustable spring clip of special design. Water is poured into P until it half fills the tubes P and O. Passing through the rubber cork at the upper end of O is the short open tube D.

The cylinder, whose contents are to be analysed, is fitted with a reducing valve, which in turn is connected by a length of rubber tubing to the brass tube T. H passes behind the wooden stand (its course is shown by dotted lines in the diagram), and reappears at G.

The absorbent pipette J and reservoir K having been charged with alkaline pyrogallate, and a strong solution of caustic soda or caustic potash having been put in the seal L, M, the next thing to do is to make some nitrogen to fill the dead space F:—Close the rubber tube below F by the spring clip E. Slip this rubber tube off the burette nozzle. Open the stop-cock B. Lower the leveller P, and thus allow air to enter the burette. Close the cock; replace the rubber tube; open F and, by raising P, force the air into the absorbent pipette J. Lower and raise P—driving the gas backwards and forwards—for several minutes. Return the residual gas to the burette, carefully lowering P until the absorbent stands at N, about half-way up the vertical tube leading from J. Close B and E. Slip the rubber tube off the burette nozzle.

The apparatus is now ready to undertake an analysis of cylinder oxygen, which is performed as follows:—

Connect G to the burette. Open B and then the cylinder valve, and allow oxygen to pass rapidly through the burette. It escapes through the water in O. (During this operation P should be held down so that the water level stands only two or three inches above G.) Let this flow of oxygen continue a few seconds until it is certain that the tubes and burette have been thoroughly cleared. Close the cylinder valve and then B. The burette is now full of oxygen. Disconnect G and re-connect F. Release the clip E. Adjust the sliding index-mark N to be exactly opposite the top of the liquid in the tube alongside it. Open B; and, by raising P, drive the oxygen into J. Continue pumping the gas backwards and forwards until it is found, on returning the gas to the burette and adjusting the liquid to the mark N, that no further diminution of volume takes place. Pumping the gas is facilitated by placing the finger on the tube D. At the end of the operation very little gas remains, and to get absorption to continue actively the water surface has to be raised into F. The facts that F is not too fine in bore, and that the upper end of J has a reduced diameter, expedite the process of absorption at the end.

The absorbent liquid having been carefully adjusted to the mark N, the residual volume is measured by raising P until the level of the water in O is the same as that in the burette. The residual nitrogen will now be at atmospheric pressure, and its percentage is read direct from the graduation on A.

Messrs. Baird & Tatlock, of Renfrew Street, Glasgow, supply both the apparatus and charges of potash-pyrogallate ready for use.
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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH.

ADVISORY COUNCIL.

SECOND REPORT

OF THE

MINE RESCUE APPARATUS RESEARCH COMMITTEE.

LONDON:
Printed and Published for the Department of Scientific and Industrial Research by His Majesty's Stationery Office.
1920.

Price 2s. 0d. Net.
PREFATORY NOTE.

The Mine Rescue Apparatus Research Committee, whose First Report was published in 1918, was appointed by the Advisory Council for Scientific and Industrial Research, on the suggestion of the Home Office, in 1917, and consists of:—

Mr. William Walker, C.B.E., Chief Inspector of Mines (Chairman).
Mr. Henry Briggs, O.B.E., D.Sc., A.R.S.M., M.I.M.E.
Mr. John Haldane, M.D., LL.D., F.R.S.

Dr. Briggs, as heretofore, has continued to direct the experimental work of the Research at the Heriot-Watt College, where facilities are provided by the kindness of the Governors of the Heriot Trust.

This Second Report of the Committee is published with the concurrence of the Home Office.

Department of Scientific and Industrial Research,
16 and 18, Old Queen Street, Westminster, S.W.1.

June, 1920.
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INTRODUCTION.

To the Advisory Council to the Committee of the Privy Council for Scientific and Industrial Research.

Gentlemen,

We beg to submit our Second Report. It relates chiefly to experimental results obtained in Edinburgh during the last two years, and to the description of new or improved methods and apparatus which are the outcome of the investigation.

By the terms of reference we are required to state whether we deem it advisable that the types of mine rescue apparatus should be standardised. We do not think that standardisation, in the sense of a prescribed uniformity of construction, is to be recommended in this instance. We prefer that the field for invention and enquiry should be left open rather than be circumscribed by a hard-and-fast specification. On the other hand (as we stated in the First Report), we hold that every type of breathing apparatus intended for use in mines should be tested very thoroughly before being officially approved for that purpose, and we consider that the manner of testing should be standardised. Building upon the general requirements of such apparatus, as set forth in our previous Report, we have drawn up a scheme of examination which we think could with advantage be adopted for testing an apparatus. The American Bureau of Mines has recently formulated a somewhat similar scheme of examination; we are indebted to the Director for kindly providing a copy of that document, which has been useful to us in drafting our own scheme. It is interesting that in respect of these apparatus the two countries should be progressing on lines so closely alike.

The requirements of our First Report (pp. 14 to 17) are very comprehensive. To avoid the criticism that our recommendations amount to a counsel of perfection, and also to carry out in the fullest sense that part of the terms of reference which gives us the task of determining by experiment what improvements in apparatus are possible, it became incumbent upon us to prove that it was feasible to devise a compressed-oxygen rescue apparatus complying with those requirements; the construction of such an apparatus was, therefore, given the leading place in the programme of work for the present financial year. In this Report we include, in Appendix I, drawings and a description of the compressed oxygen apparatus designed by Dr. Briggs, and an account of the tests to which the first model has been subjected. No claim of finality is made on behalf of this apparatus; it embodies several points of design in existing apparatus and will itself doubtless be improved in the light of further experience.

Down to the time of writing we have given much less attention to liquid air rescue apparatus than to those depending on compressed oxygen. There are two reasons for postponing work on the former type: first, as conditions now stand, there are over seventeen times as many compressed oxygen as liquid air apparatus in use in this country, and the type in greater vogue must naturally take precedence; secondly, our suggestion that a separate research committee be set up to investigate the problems of the supply and transport of liquid and gaseous oxygen was adopted by you, with the result that the Oxygen Research Committee was established in 1918, first under the auspices of the War Priorities Committee.
and now under the Department of Scientific and Industrial Research—which Research Committee is actively considering many questions bearing on the utilisation of liquefied air and oxygen. As so much of the work of the Oxygen Research Committee, and of the War Office and Air Ministry, on the subject of liquid air is bound to be of the greatest value to us, we deem it politic to allow those more general investigations time to mature before attempting to experiment systematically on the narrower problem of liquid air rescue apparatus. Experience has, however, shown that, apart from certain difficulties of transport, this type of apparatus can be made thoroughly serviceable, and we propose to devote further attention to it in the near future.

The present Report consists of four parts. In the first of these—the physiological side of the subject is discussed more completely than hitherto, and an abridged account is included of some important new physiological facts which were discovered in the course of the experiments. In Parts II-IV we deal mainly with matters alluded to in the First Report, the need having arisen, as the result of special experience or experiment, of re-treating or enlarging upon certain aspects of the inquiry. Appendix II, by Dr. Briggs, describes a method of measuring physical fitness which evolved, during 1918, from tests on trained rescue men in Edinburgh. A Physical Test Station was established in Edinburgh to apply this method in testing the physical capabilities of recruits and others sent in from Army Units stationed in that military area. The Test Station was in the University buildings, and had a small military staff under Dr. Briggs superintendence; it commenced operations in August, 1918, and ceased its active life at the Armistice, in November. Although an outcome of the research a Mine Rescue Apparatus, an exhaustive account of the experiments on physical exertion and of the work of the Test Station would be out of place in such a Report as this; with your permission, it is, therefore, proposed that Dr. Briggs should immediately prepare a paper for the Royal Society of Edinburgh in which to treat of the matter more completely. A short preliminary paper by Dr. Briggs entitled "Fitness and Breathing during Exertion," was read before the Philosophical Society in July, 1919.

In the autumn of 1918, Lieut.-Colonel Raper, of the Anti-Gas Department Ministry of Munitions, proposed that there should be a closer connection between his Department and the research, and offered to appoint Lieutenant Rosling a liaison officer. We cordially welcomed that proposal, and take this opportunity of thanking the Anti-Gas Department for Lieutenant Rosling's services, which have been of decided value to us since he was transferred to Edinburgh. We refer again, on a later page, to the connection between the two investigations.

Miss Elizabeth Gilchrist, M.A., B.Sc., and Mr. David Penman, B.Sc., who assisted Dr. Briggs since July, 1917, have recently accepted other posts; the former as Carnegie Research Fellow in the University of Edinburgh and the latter as Lecturer in Mining in the St. Helen's Technical Institute. We are sorry to lose the help of these expert assistants, who gave two years of loyal work to the research. In September, 1918, Mr. Penman read an excellent digest of the First Report before the Institution of Mining Engineers, and the ensuing discussion was of much value.

Mr. F. J. McConnell has been elected in Mr. Penman's place.

We are also sorry to lose the valuable services of Mr. A. Richardson, who has been appointed Principal of the School of Metalliferous Mining, Cornwall. Mr. E. Barnard takes Mr. Richardson's post as Secretary to the Committee.

We are indebted to Mr. James A. Hood, Mr. Mungo Mackay, and other officials of the Lothian Coal Company for their kindly help in carrying out underground respiration experiments, and to a large number of mine and rescue station officials, miners, army officers and men who so willingly acted as subjects in tests which were often of an exacting description.

We have again to record our appreciation of the valuable assistance rendered by the Governors of George Heriot's Trust in granting facilities for the research in the Heriot-Watt College, Edinburgh.
PART I.
PHYSIOLOGICAL CONSIDERATIONS AND EXPERIMENTS.

Physiology stands in much the same relation to breathing apparatus as physics does to the steam engine; and a condensed statement of the physiology of breathing and its accompanying effects and reactions is, we think, as necessary here as the treatment of thermodynamics in a modern book on steam. Several of the defects of existing rescue apparatus alluded to in our First Report are due to a disregard, or false appreciation, of certain physiological laws, which, when thoroughly grasped, are capable of materially assisting the designer of such apparatus.

The ventilation of the lungs by breathing has a dual purpose: it supplies oxygen to the blood and removes excess of carbon dioxide from it. The blood, in its turn, carries oxygen to all parts of the system, and conveys back to the lungs the carbon dioxide, which is the chief (though not the only) waste product of that breaking-down of tissue which goes on as long as life lasts. The muscular contractions, which enable us to do external work in giving potential or kinetic energy to ourselves or to some separate body, involve an increase in tissue destruction, which results in a demand for a more energetic clearance of the CO₂ produced and for an enhanced oxygen intake. Unless the exertion is excessive or the oxygen supply inadequate—cases which are separately considered below—the demand is fully met by the lungs of a healthy person in increased breathing and by the heart in increased blood-circulation.

Normal Respiratory Control.—The spongy distensible organs we call the lungs consist of a branching system of tubes (bronchi) ending in air sacs (alveoli) which are surrounded by a cellular membrane (epithelium). Breathing causes an alternating flow of air in the bronchi and so ventilates the air sacs; on inspiration, oxygen is carried into them; on expiration, carbon dioxide is carried out. The epithelium separates the air in the alveoli and the blood which courses in countless capillaries on the inner side of that membrane. The gaseous exchange—oxygen to the blood and CO₂ from it—is thus conducted through the epithelium.

Haldane and Priestley* showed that, in normal conditions near sea-level and with the subject at rest, the respiration is so adjusted as to keep constant the CO₂ percentage in the alveolar air at a figure which varies with different individuals, but which averages 5-6 for men.

It is important to realise the fact that under normal conditions, when resting, the factor controlling breathing is the concentration of CO₂ in the blood. The part of the brain known as the "respiratory centre," which directs the movement of the lungs, receives its incentive from the CO₂-saturation of the blood passing through it, and it controls matters (with an almost inconceivably delicate degree of regulation) so as to maintain that saturation at a constant level. If the blood should become over-concentrated in CO₂, enhanced breathing (hyperpnoea) results, and continues until the excess is removed; if for any reason the degree of saturation is reduced below normal, there is a cessation of breathing (apnoea) until the deficiency disappears.† The respiratory centre must evidently be regarded as a very sensitive governor of the CO₂ pressure in its own substance, and indirectly in the arterial blood and alveolar air. We may compare its action to that of the governor of an engine, if we may bear in mind that the respiratory centre governs CO₂ percentage, whereas the governor of the engine controls its rate of revolution.‡

The fact that CO₂, and not oxygen, normally dominates the respiratory centre was strikingly illustrated in a famous experiment of Professor Yandell Henderson. He subjected an animal to prolonged artificial respiration, so as to swell out most of the CO₂ in solution in the blood. When the animal was left to itself, apnoea was so profound that it died of want of oxygen before breathing recommenced.

Extended study of this problem of breathing control reveals that other acid compounds as well as CO₂ are able to stimulate the respiration when introduced into the blood—a principle to which we shall recur in discussing the meaning of certain experimental results.

Nearly all the carbon dioxide is conveyed by the blood as unstable bi-carbonates, and passes through the epithelium into the alveoli. The haemoglobin (red pigment) is the main oxygen carrier of the blood. In small quantities both nitrogen and oxygen are taken up in ordinary solution, but when breathing normal air at normal pressure, the amount of oxygen borne in this way is, as a source of supply, of little account. Haemoglobin enters into a definite, though unstable, chemical union with the oxygen, and it is as “oxyhaemoglobin” that oxygen is mainly carried by the blood. If the active haemoglobin is reduced in amount, say by breathing air containing carbon monoxide, collapse, loss of consciousness or death may ensue from oxygen starvation.

Effects of Breathing Air rich in Oxygen.—When a man wears a rescue apparatus, the percentage of oxygen in the apparatus may easily rise over 90. The influence on his ability to undertake physical work when breathing air enriched to such a degree has been studied by us with some care, and on a later page a short account is given of the results obtained. Two other effects fall to be noted at this place:—The first of these is due to the high partial pressure of oxygen in the air inhaled, which brings about an increase in the proportion of oxygen carried in ordinary solution by the blood as distinct from that carried in chemical combination by the haemoglobin. The bearing of this effect in retarding the consequences of inhaling CO, and in explaining the efficacy of administering oxygen to a person suffering from CO poisoning, has already been dealt with in the First Report, p. 16.

Discharge of Nitrogen from the Blood.—The second is that, simultaneously with the taking up of oxygen in solution, there is a discharge of nitrogen from the blood, since the partial pressure of nitrogen in the alveolar air is greatly reduced. Thus we have in the blood itself an additional source of nitrogen. In the closed circuit of a rescue apparatus, the nitrogen so expelled remains in the apparatus unless voided through the relief valve. As blood-nitrogen is only discharged when the oxygen percentage is increasing in the inhaled air, and as it is limited in volume, it does not contribute in any way to the risks of using rescue apparatus. Indeed, providing that a start is made with the apparatus full of oxygen and that the further precaution is taken of swilling it out now and then with the by-pass, the expulsion of the blood-nitrogen makes slightly for safety; for should the oxygen proportion in the inhaled air sink at any subsequent time, the blood will remove some of the accumulating nitrogen by re-solution.

Fallacious Views as to Effects of Breathing Oxygen.—The entirely incorrect view that oxygen is a “dope,” and that the breathing of highly enriched air results in a rapid burning up of the tissues accompanied by excitement and violent bursts of physical energy, or that it is followed by depression and lassitude, is still held by many people. We find the fallacy to persist even among rescue station instructors, and we cannot regard without misgiving its influence on their method of using breathing apparatus. Purposely to retain nitrogen in the bag in order to prevent the wearer getting “too much oxygen” is to run grave risks (see First Report, pp. 20 and 26). One of the difficulties encountered in introducing oxygen apparatus for high-altitude aeroplane flying is the antipathy of many airmen to what they consider to be the drug-like properties of the gas. It ought not to be necessary to state to those habitually using rescue apparatus that there is not the least evil effect or objection of any kind attending the breathing of pure or almost pure oxygen even for several hours, and that the alleged consequences referred to above are altogether fictitious. On the contrary, fatigue is appreciably lessened by oxygen inhalation as will be shown below.

* In air containing 21% of oxygen, the partial pressure of that gas is 0.21 of an atmosphere or 150 mm. of mercury. In air containing 90%, the partial pressure is 0.90 of an atmosphere or 684 mm. of mercury.
It is only when air containing over 80 per cent. oxygen is breathed continuously for over two days that evil effects make themselves felt. Professor Lorrain Smith was the first to show that inflammation of the lungs may be produced in animals if they are kept in such an atmosphere for at least two days.

Transference of Oxygen from the Air to the Blood.—We have yet to refer to the manner in which the oxygen reaches the blood through the epithelium. The physical laws of diffusion do not explain the phenomena of blood-oxygenation when the subject is making a special demand on oxygen supply either because he is doing physical work or because, as airman or mountaineer, he is breathing rarefied air. The results obtained in 1911 during a month’s sojourn on the summit of Pike’s Peak, Colorado, (14,000 ft.)* may usefully be mentioned. They made it clear that the system is able to adapt itself to the lowered pressure, so that it can obtain, without distress, a sufficiency of oxygen. It was found that, to secure the necessary supply, the pressure of oxygen in the arterial blood rose higher than the partial pressure of oxygen in the atmosphere—a state of affairs which cannot be explained on the assumption that the oxygen input to the blood is altogether the result of gaseous diffusion. Though admittedly standing now on controversial ground, the evidence strongly supports the view that the epithelium is not a mere porous diaphragm, but that the living cells from which it is built possess the faculty—which they exercise at need—of secreting oxygen from the air and of handing it forward at enhanced pressure to the blood. There seems, indeed, little doubt that this attribute of secretion can be developed or improved (especially in a young person) by physical training or by adaptation to low oxygen pressure.

Effects of Oxygen-want and CO₂-excess on Breathing.—It has been proved that, when a person is caused to breathe air containing several parts per cent. of CO₂, an increase in the depth of breathing results, though the rate may remain constant until the CO₂ mounts up still higher.

In considering the influence of oxygen-want care must be taken to distinguish between the effect of breathing air having a reduced oxygen percentage and that resulting from fatigue. As will be shown below, respiratory fatigue produced, e.g., by resirling against resistance, creates a type of breathing which develops oxygen-want; at this point, however, we consider the simpler case in which the lack of oxygen is produced solely by deficiency of oxygen in the inspired air.

When a man begins to breathe air poor in oxygen, the response of the respiratory control differs according to the degree of oxygen-want. If the latter be slight, "periodic breathing" often sets in, this being characterised by the breathing becoming excessive and dying away in alternating succession. If the lack of oxygen be more pronounced, the breathing is fairly regular but more rapid, though much less deep than when it is stimulated by CO₂.

From the point of view of the user of breathing apparatus, it is enough to remember that excess of CO₂ induces deep and slow, and oxygen-want quick and rather shallow, breathing.

Shortage of oxygen takes effect much more quickly than CO₂ excess, since the body has practically no storage capacity for oxygen while it has a great deal for carbon dioxide.

The Effects of Breathing against Resistance.—In the First Report (p. 17) we referred to the causes and to the physical results of excessive resistance in the breathing circuit of a rescue apparatus, in regard both to the enhanced risk of leakage and to the discomfort of the wearer. We now propose to consider briefly the physiological effects of resistance. The subject has recently been investigated by Davies, Haldane and Priestley.†

When a resistance to breathing is thrown in, the first effect is that the breathing movements are slowed. As a consequence of this CO₂ begins to accumulate to

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† Jour. of Physiol., III, 1919.
an abnormal extent in the lungs, and consequently in the arterial blood. A very slight accumulation, however, suffices to make the breathing more energetic and deeper, so that as much air is breathed as before, though the frequency of breathing is diminished and the depth correspondingly increased. In this way moderate resistances are easily compensated for automatically, even during the greatly increased breathing which accompanies muscular exertion.

When, however, the resistance is heavy, the excess of CO₂ which is required in the lung air in order to stimulate the breathing sufficiently becomes very marked, and finally fatigue of the breathing begins to show itself through the fact that the breathing becomes more and more frequent and shallow. With the increasing shallowness the penetration of fresh air into the lungs becomes less and less effective; and unless relief comes symptoms of asphyxia develop.

As might be expected, fatigue of breathing occurs much more readily during muscular exertion, when a large amount of air has to be breathed, than during rest. In consequence of this fact continued muscular exertion may easily be rendered impossible by undue resistance to breathing. It must also be borne in mind that when resistance is due to tubes, valves, or passage of air through coarsely divided material, the resistance increases as the square of the rate of air-flow. It is, therefore, the resistance to air-flow during muscular exertion that needs special attention in connection with mine rescue apparatus. This resistance ought to be so low that, even during prolonged exertion, symptoms of fatigue of breathing do not appear. There is no need to try to abolish resistance entirely, but only such resistance as will materially hamper a man's power of making such exertions as he may be called on to make continuously while using a mine rescue apparatus. We think that the exertion of walking continuously at the rate of four miles per hour may be taken as a standard test in this respect.

A man who is in poor physical training develops respiratory fatigue much more easily than a man in good training. This appears to be due largely to the fact that in the former, as shown in another section of this Report, the absorption of oxygen by the lungs during exertion is less perfect, and that any shortage of oxygen in the blood precipitates respiratory fatigue, as is proved in the paper first referred to. In the case of a man wearing a mine rescue apparatus and breathing nearly pure oxygen, this cause of respiratory fatigue is, however, annulled, so that with the same amount of work the man in poor training develops less respiratory fatigue when he is wearing the apparatus than when he is breathing ordinary air.

In different individuals the susceptibility to respiratory fatigue from resistance varies considerably, some persons being able to stand much greater resistance than others. Some, indeed, appear to be quite exceptionally sensitive to resistance. For this reason it is impossible to state for all persons the amount of resistance which is harmful, though, at a later page (p. 22), we have suggested a figure (viz., 3 ins. of water gauge under a constant rate of flow of 86 litres of air per minute) as the limiting resistance of a rescue apparatus circuit. With most people such a degree of resistance is not detrimental, and if, during the walking test with an apparatus complying with that specification, any man is found to be so sensitive that he shows signs of respiratory fatigue, we think that he ought not to be accepted as a member of a rescue team. This criterion would automatically exclude many older men.

Physical Exertion.—The requirements and limitations of what is often called the human machine are of such importance to those dealing with rescue apparatus that it becomes as necessary to study the man in his character of prime mover of agent for doing mechanical work as to study the apparatus itself, and we have devoted considerable time to this aspect of the subject.

Oxygen Supply to Muscles at Work.—The all-important question of oxygen supply to the tissues is controlled by two factors, namely, the rate at which the gas can be absorbed by the blood in the lungs and the rate at which the oxygenated blood can be delivered to the muscles doing work. The supply can only be effectual when the lungs and heart act in accord, for the failure of either adequately to meet the demands of the moment may render nugatory the fullest effort on the
part of the other. For example, the breathing of an exhausted athlete, though it may be 15 or 18-fold that of his resting condition, does not of itself suffice to enable him to continue his exertion in face of inadequate circulation. Here the circulatory, and not merely the respiratory, system is at fault.

Instances of the opposite kind, namely, those in which distress is produced by the rate of oxygenation of the blood failing to keep pace with muscular demands though the circulation may be adequate, are of great practical interest. They include the case of the poison-gas patient (where the epithelial layer of the lungs is so thickened as to make oxygen-penetration difficult), the case of the high-flying airman (when the low barometric pressure and correspondingly low partial pressure of the atmospheric oxygen prevent proper oxygenation of the blood), and that of the so-called D.A.H. patient, where the extreme shallowness of breathing impairs the transfer of oxygen to the blood by insufficient exposure of epithelial area to the inhaled air. In the cases enumerated the inhalation of highly enriched air is immediately beneficial, and the means of administering it under a variety of conditions has been during the war, and still is, the subject of active study.

Fatigue.—The causes of the fatigue which results from heavy muscular exertion have not yet been fully analysed; but the experiments of Dr. Briggs, to be described presently, throw a very important new light upon them. During heavy muscular work the consumption of oxygen and production of CO₂ by the whole body are increased about ten times or even more. In the working muscles there must be a far greater proportional increase in consumption. The increase can only be obtained by an enormous increase in the circulation of blood through the muscles; and it is clear that, if an increased circulation cannot be brought about, the muscles themselves must fall from want of oxygen. Now it is known that when muscles are insufficiently supplied with oxygen they produce, and give off to the blood, lactic acid instead of CO₂. With a very excessive muscular exertion, such as running quickly upstairs, the circulation is completely inadequate to meet the oxygen-requirements of the over-taxed muscles; and it has been shown experimentally that the blood is at once flooded with lactic acid. This acid acts just like CO₂ on the respiratory centre, but, unlike CO₂, is not rapidly removed from the blood by the lungs. As a consequence, intolerable panting is produced, and the exertion is brought to a speedy end, partly by the ensuing distress, partly by failure of the muscles, and partly also by the general action of the abnormal blood in paralysing the central nervous system and thus causing stupor or even loss of consciousness.

With more moderate exertion the blood-supply to the muscles can be properly maintained, so that little or no lactic acid passes into the blood. Yet fatigue may develop rapidly, the most prominent symptom being distress as regards breathing. It is on this form of fatigue that, as will be seen below, the new experiments throw a flood of clear light.

Nature of Physical Work.—Every-day experience assures one that a muscular task is easier when one is in good condition. It is equally certain that even a light task, involving external work, though easy to commence with, cannot be continued indefinitely without pause, and that the heavier the labour the shorter the time it can be sustained. Nevertheless, there are certain lesser degrees of exertion (for instance, cycling or walking at a moderate pace on a flat road) which, by the ease with which they can be kept up for hours on end, may be referred to, in electrical engineers' phraseology, as "normal loads"; while other and heavier tasks (for example, hard bayonet exercise or running quickly upstairs) are bearable for a limited period only, so that "overload" may permissibly be applied to them.

What may be an overload to one person is a normal load to another who is stronger or in better training or more habituated to the particular kind of labour. Again, a normal load when a person is fit may prove to be an overload when he is unfit; and, as has been remarked, even an easy, normal load, if long supported without rest, will eventually become an overload, and then the exertion has to be interrupted. It is evident, then, that the whereabouts of the dividing line between
a normal and overload for any individual depends on his condition at the time; if he is getting tired, it is moving down the scale of exertion; if resting, it is moving up.

**Effects of Breathing Enriched Air.**—It is well known that when air enriched with pure oxygen is breathed by a normal individual during rest there is no noticeable effect. When, however, a rescue apparatus is being used, the wear is often doing pretty hard physical work. The effects of the extra oxygen during exertion have been carefully observed by Dr. Briggs in the course of the investigation, and the results throw a quite new light on fatigue.

It had often been observed before that some persons using a rescue apparatus derive great benefit during exertion from the enriched air. For instance, they can walk faster and more comfortably, in spite of the weight of the apparatus. This advantage is very marked in the case of two of us who have frequently experimented with rescue apparatus of every type. When, however, the enriched air was tested on practical miners, it was found that they seemed to derive little, or no benefit from it. Their breathing was then investigated more closely, the expired air being collected in bags, measured and analysed. The very striking fact then appeared that, when ordinary air is breathed, the expired air of men or other men in equally good physical training contains, during exertion, a much higher percentage of CO₂ and lower percentage of oxygen than that of men who are not in good training. In other words, less air is breathed by men in good training for a given consumption of oxygen or amount of work. There is, however, little or no difference in this respect when enriched air is breathed, unless the work is pushed to an extreme point. On the other hand, with men not in good training the percentage of CO₂ in the expired air becomes as high during exertion as in the men in training, so that the amount of air breathed for a given rate of work is considerably less with enriched air than with ordinary air. The following Table, showing the results for two typical individuals, illustrates these points:—

**Table 1.**

<table>
<thead>
<tr>
<th>Work in ft. lbs. per min.</th>
<th>Pet. cent. CO₂ in expired gas</th>
<th>Litres gas expired per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subject A Breathing air</td>
<td>Subject B Breathing air</td>
</tr>
<tr>
<td>Pedalling with brake off</td>
<td>Breathing oxygen</td>
<td>Breathing oxygen</td>
</tr>
<tr>
<td>3,000</td>
<td>4.65</td>
<td>5.25</td>
</tr>
<tr>
<td>6,000</td>
<td>4.7</td>
<td>5.8</td>
</tr>
<tr>
<td>9,000</td>
<td>4.3</td>
<td>5.8</td>
</tr>
<tr>
<td>10,000</td>
<td>4.1</td>
<td>5.7</td>
</tr>
<tr>
<td>12,000</td>
<td>—</td>
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</tr>
</tbody>
</table>

How is the effect of enriched air on persons not in good training brought about, and why do those in good training respond so little to the enriched air? The answer to this question appears to be a very definite one. Recent investigations have shown that, during rest under normal conditions, the haemoglobin of the blood passing through the lungs has time to take up by the mere physical process of diffusion all the oxygen it is capable of taking up. When, however, during muscular

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* It was found by experiment that, even with the least fit person, no advantage was to be secured by increasing the percentage of oxygen above 60. At the Physical Test Station, a regular oxygen proportion of two-thirds was obtained by causing the oxygen, after passing from the cylinder through a reducing valve, to issue from an injector nozzle. The injector drew in outside air through a small pipe controlled by a tap, and the tap was set by trial (and then soldered in position) so that the mixture passing forward to the receiving bag (from which the subject drew his supply) was 60 per cent. air. Allowing for impurity in the cylinder oxygen, such a mixture holds about 57 per cent. oxygen. This arrangement saved a good deal, oxygen being the main item of expense of the Station.

exertion, a far larger amount of oxygen has to be taken, there is not time for the haemoglobin to become fully saturated by diffusion alone if ordinary air is breathed, and, unless the epithelium lining the alveoli actively passes oxygen inwards, the arterial blood is imperfectly saturated with oxygen, and this makes the breathing faster and tends, as already mentioned, to exhaust the breathing powers. But the activity of the epithelium can be increased by practice. Hence, in men who are accustomed to muscular exertion, there is no deficiency of oxygen in the arterial blood when ordinary air is breathed until exertion is pushed to the utmost. For this reason they also receive no benefit from breathing air enriched with oxygen. On the other hand, in men who are not accustomed to muscular exertion, the epithelium fails to pass in the proper supply of oxygen unless the diffusion pressure of oxygen is raised in the alveolar air by the enriched inspired air. Hence these persons benefit by enrichment of the air with oxygen.

It would be out of place to attempt to discuss here all the evidence which supports this interpretation of the new facts described above; but in the present state of knowledge, no other interpretation seems at all probable. To produce the beneficial effects of the enriched air, it is not at all necessary that pure oxygen should be breathed. All that appears to be needed is air containing a considerably higher percentage of oxygen than ordinary air. It has often been observed by engineers that men work in compressed air (in caissons and in tunnels under water during construction) more easily than in ordinary air. In this case also the diffusion pressure of oxygen in the lung alveoli is increased by the compression. An investigation of their breathing would reveal the same phenomena as in the case of men using mine-rescue apparatus.

It is evident that the physiological response of a man to oxygen during muscular exertion furnishes an interesting test of whether or not he is in good training as regards his lungs. Physiological fitness depends not only on the lungs, but also on ready adaptation of the circulation, muscles, nervous system, &c., to whatever exertions are required. It is possible, therefore, that a man might be in a "fit" state as regards his lungs, but not fit otherwise. A stay at a high altitude, where the reserve power of the lungs is called upon even during rest, might, for instance, produce this condition. In ordinary cases, however, lung fitness is an accomplishment of general physical fitness, and may therefore be taken as a measure of it. Dr. Briggs has applied the new facts as the basis of a method of testing physical fitness; and this method was used during some months for Army purposes, as already mentioned. The same method is, of course, also applicable for the testing of members of a rescue brigade. A description of how this method can be carried out is therefore given in Appendix II.

Climbing, Walking and Running Tests.—(1) Climbing Tests at Newbattle and Lingerwood.—The first climbing experiments of this kind were made by Drs. Haldane and Briggs in November, 1917, in the Newbattle and Lingerwood pits of the Lothian Coal Co., Ltd., and their purpose was solely to determine the oxygen consumption while climbing mine inlines of different gradients, and while breathing ordinary air. To make the results more useful for rescue apparatus purposes, the subjects of the tests carried rescue apparatus in addition to the Douglas outfit (see Appendix II). The air of the roadway was in each case inhaled, the exhaled products being discharged over a timed period into the Douglas bag, which was carried on the chest. The volume of the bag was metered on the spit and samples of the air taken. Some of the samples were analysed by means of a Haldane apparatus fitted up in a pump-room underground, while others were dealt with in Dr. Briggs' laboratory. The experiments should be regarded as preliminary to the Burdiehouse tests described below. The table on p. 20, First Report, gave a summary of these results.

(2) Climbing Tests at Burdiehouse.—During the early part of 1918, a number of experiments were made on men climbing the main incline of the Burdiehouse lime-stone mine, both while breathing air and while breathing oxygen. The earlier tests, alluded to above, had shown the desirability of limiting the variables. This could be done either by taking one subject on a number of gradients, or by taking
a number of subjects on one incline, and the latter alternative was chosen as being likely to give more information. The Burdiehouse incline lies at the uniform angle of 21°. The roof is high, so that there was no occasion to stoop, and the floor while dry for the most part, was, at the time of the tests, wet and slippery in places. On the whole, the "going" may be taken as a fair average of that in a mine roadway of heavy gradient.

Including, as it did, oxygen cylinders, meters, bellows, rescue apparatus, Douglas outfit, gas analysis apparatus, sample bottles, mercury, &c., a considerable equipment had to be carried by motor-car to the mine and then into the road. The physical difficulties involved made rapid work impossible, and we had to be satisfied with a comparatively few determinations for each subject. Usually values were obtained at five rates of speed, both when breathing air and when breathing oxygen.

During the Burdiehouse climbing tests the manner of use of the Douglas differed from the usual in that the bag was made the reservoir out of which the man drew air or oxygen during the timed period, instead of being a receptacle for expired air. At the commencement of a test this bag was inflated with a measured volume of air or oxygen. In the case of air a large double acting smoke-helmet bellows was used to supply the air, while in that of oxygen the gas was admitted, through a dry meter, from a small cylinder. The expired air or oxygen was made to pass into a Proto bag hung in front, over the rescue apparatus bag, and fitted with an automatic relief valve.

When breathing air, the subject walked at the desired rate up the incline (which was marked-off in chains and poles) until it was judged that his respiration had adjusted itself to the degree of exertion; the 3-way tap was then turned and air drawn from the Douglas bag until that bag was almost empty when the tap was turned off and the mouthpiece at once removed so as to conserve the expired products collected in the Proto bag. Samples were then drawn from the latter, and the volume of air remaining in the Douglas bag was measured.

Before any values were obtained on oxygen, the subject was required to use the rescue apparatus for some time in order to wash out the bulk of the free nitrogen dissolved in the blood and tissues. During this period the nitrogen was expelled from the rescue apparatus by using the by-pass from time to time. He was not permitted to breathe air again until the whole of the oxygen series was completed; during spells of rest, and during the first part of a climb while his respiration was accelerative, he used the rescue apparatus. On switching to the Douglas bag he rapidly changed mouthpieces, an operation which was repeated the moment the exertion was stopped.

All distances are recorded on the incline and not on the flat. The extra work performed per minute was evaluated in ft. lbs. by multiplying the gross weight in lbs. (man plus apparatus carried) by the rise in feet per minute.

The weight carried was the same, within a pound or two, for every subject, as averaged 43 lbs.

(3) Walking and Running Tests.—These were conducted in the observatory court (level cement floor) of the Edinburgh Rescue Station, the appliances as routine being the same as those of the Burdiehouse tests.

Oxygen Consumption during Exertion.—A full account of the experiments with the ergometer and on men climbing, walking and running will be given in separate paper now being prepared for the Royal Society of Edinburgh. It is, however, advisable here to set forth in tabular form the oxygen consumed determined in these experiments, since the question of oxygen supply during physical exertion is of the first importance to the designer or user of mine rescue apparatus. Attention is directed to the variations in oxygen consumptions between one man and another, and to the high figures sometimes reached.

A description of Subjects I, II, V, VII, and VIII is given in Appendix II; the following facts relate to the others included in the tables:

Subject III.—Rescue station instructor; weight, 165 lbs.; fitness (from ergometer test), 80 per cent.
Subject IV.—Mine under-manager: weight, 168 lbs.; trained rescue man; engaged in a pit working flat seams; fitness 64 per cent.

Subject VI.—Army recruit, previously bank clerk: weight, 142 lbs.; fitness, 42 per cent.

Subject IX.—Mine fireman in a pit working flat seams: weight, 168 lbs.; trained rescue man; fitness 69 per cent.

Subject X.—Featherweight boxing champion of Great Britain, working as a riveter at time of test; not in fighting training; weight 133 lbs.; fitness 77 per cent.

Subject XII.—Army officer: fitness, 93 per cent.

Subject XIII.—First-class footballer, runner, jumper and all-round athlete, Army instructor in physical drill; weight 158 lbs. Records were obtained on this subject in three conditions—(1) in good health; fitness 70 per cent. (the ergometer results labelled (a) were obtained on this occasion); (2) in good health and after intensive physical training at Aldershot; fitness 100 per cent.; and (3) in poor health; fitness 55 per cent. The climbing and walking tests and also the ergometer tests marked (b) were carried out with the subject in the last condition.

Subject XIV.—Army officer doing sedentary duty; had been wounded through the groin; weight, 161 lbs.; fitness, 62 per cent. Formerly a long distance runner.

Subject XV.—Rescue station assistant instructor: weight, 147 lbs.; fitness, 93 per cent.

Subject XVI.—Research assistant: sedentary habits; weight, 154 lbs.

Subject XVIII.—Instructor in physical drill at an officers' hospital; weight, 156 lbs. Fitness deteriorating: 56 per cent.

Subject "C.G.D."—The information relating to this subject (a) when walking at different rates on a laboratory floor, and (b) when walking in a grass field, have been extracted from Haldane and Douglas' paper entitled "The Capacity of the Air Passages under varying Physiological Conditions" (Journ. Physiol. 45, 1912, p. 235) and are given here for the sake of comparison. To make the oxygen consumptions more strictly comparable with our determinations, it has been necessary to add 25 per cent. to the published figures to allow roughly for the fact that the subject did not carry a weight of 43 lbs. in addition to the Douglas outfit.

The oxygen consumed is, in all cases, expressed in litres per minute, the gas being dry and at 32° F. (0° C.) and 30 ins. barometer.

**Table 2.**

**Oxygen Consumption.**

Walking and Running on the Flat, carrying weight of 43 lbs.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Standing</th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
<th>5.</th>
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<tbody>
<tr>
<td></td>
<td>Breathing Air</td>
<td>Breathing O₂</td>
<td>Breathing Air</td>
<td>Breathing O₂</td>
<td>Breathing Air</td>
<td>Breathing O₂</td>
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<tr>
<td>I</td>
<td>.71*</td>
<td>.68*</td>
<td>.77</td>
<td>.91</td>
<td>.85</td>
<td>1.14</td>
</tr>
<tr>
<td>II</td>
<td>.47</td>
<td>.53</td>
<td>.59</td>
<td>.59</td>
<td>.80</td>
<td>.74</td>
</tr>
<tr>
<td>III</td>
<td>.25</td>
<td>.41</td>
<td>.64</td>
<td>.47</td>
<td>.90</td>
<td>.70</td>
</tr>
<tr>
<td>XII</td>
<td>.31</td>
<td>.28</td>
<td>.60</td>
<td>.63</td>
<td>.88</td>
<td>.60</td>
</tr>
<tr>
<td>XVI</td>
<td>.35</td>
<td>.37</td>
<td>.70</td>
<td>.81</td>
<td>.92</td>
<td>1.22</td>
</tr>
<tr>
<td>Average</td>
<td>.40</td>
<td>.45</td>
<td>.66</td>
<td>.69</td>
<td>.87</td>
<td>.96</td>
</tr>
</tbody>
</table>

(a) 40  | 40  | 60  | 84  | 1.14 | 1.47 | 2.65 |

(b) 40  | 40  | 67  | 98  | 1.33 | 1.99 | 3.17 |

* Unusually high; omitted in averaging.
† Interpolated from the graph.
TABLE 3.
Oxygen Consumption.
Climbing Mine Incline of 21°, carrying 43 lbs.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Breathing Air</th>
<th>Breathing Oxygen</th>
<th>Work done in Foot-pounds per Minute.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standing</td>
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<td>6,000</td>
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<td>.62</td>
<td>.57</td>
<td>1.08</td>
</tr>
<tr>
<td>II</td>
<td>.42</td>
<td>.40</td>
<td>1.14</td>
</tr>
<tr>
<td>III</td>
<td>.35</td>
<td>.41</td>
<td>1.14</td>
</tr>
<tr>
<td>XII</td>
<td>.47</td>
<td>.45</td>
<td>1.40</td>
</tr>
<tr>
<td>XVI</td>
<td>.45</td>
<td>.47</td>
<td>1.24</td>
</tr>
<tr>
<td>Average</td>
<td>.46</td>
<td>.46</td>
<td>1.20</td>
</tr>
</tbody>
</table>

TABLE 4.
Oxygen Consumption.
Climbing Mine Incline of 21°, carrying 43 lbs.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Breathing Air</th>
<th>Breathing Oxygen</th>
<th>Speed in Miles per Hour; Slope Measurement.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standing</td>
<td>0.5.</td>
<td>1.0.</td>
</tr>
<tr>
<td>I</td>
<td>.62</td>
<td>.57</td>
<td>1.10</td>
</tr>
<tr>
<td>II</td>
<td>.42</td>
<td>.40</td>
<td>1.16</td>
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<td>III</td>
<td>.35</td>
<td>.41</td>
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<td>.47</td>
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<td>1.50</td>
</tr>
<tr>
<td>XVI</td>
<td>.45</td>
<td>.47</td>
<td>1.26</td>
</tr>
<tr>
<td>Average</td>
<td>.46</td>
<td>.46</td>
<td>1.24</td>
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TABLE 5.
Oxygen Consumption.
Ergometer Results.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Breathing Air</th>
<th>Breathing</th>
<th>Breathing</th>
<th>Breathing</th>
<th>Breathing</th>
<th>Breathing</th>
<th>Breathing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standing</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
<td>O₂</td>
</tr>
<tr>
<td>I</td>
<td>0.28</td>
<td>0.31</td>
<td>1.23</td>
<td>1.05</td>
<td>1.77</td>
<td>1.55</td>
<td>2.42</td>
</tr>
<tr>
<td>II</td>
<td>0.23</td>
<td>0.31</td>
<td>1.23</td>
<td>1.20</td>
<td>2.08</td>
<td>1.82</td>
<td>2.42</td>
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<tr>
<td>III</td>
<td>0.37</td>
<td>0.22</td>
<td>1.03</td>
<td>0.81</td>
<td>2.03</td>
<td>1.60</td>
<td>2.20</td>
</tr>
<tr>
<td>IV</td>
<td>0.33</td>
<td>0.26</td>
<td>1.12</td>
<td>0.65</td>
<td>1.68</td>
<td>1.01</td>
<td>2.04</td>
</tr>
<tr>
<td>V</td>
<td>0.28</td>
<td>0.37</td>
<td>1.17</td>
<td>0.81</td>
<td>1.80</td>
<td>1.44</td>
<td>—</td>
</tr>
<tr>
<td>VI</td>
<td>0.47</td>
<td>0.40</td>
<td>1.17</td>
<td>1.02</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>VII</td>
<td>0.45</td>
<td>0.40</td>
<td>1.13</td>
<td>1.05</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>VIII</td>
<td>0.42</td>
<td>0.32</td>
<td>1.05</td>
<td>0.97</td>
<td>1.78</td>
<td>1.39</td>
<td>2.27</td>
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<td>IX</td>
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<td>0.20</td>
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<td>0.95</td>
<td>1.88</td>
<td>1.32</td>
<td>2.30</td>
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<td>X</td>
<td>0.37</td>
<td>0.28</td>
<td>1.12</td>
<td>0.81</td>
<td>1.83</td>
<td>1.28</td>
<td>2.02</td>
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<td>XII</td>
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<td>0.41</td>
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<td>0.92</td>
<td>1.58</td>
<td>1.51</td>
<td>3.2</td>
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<td>XIII(a)</td>
<td>0.33</td>
<td>0.45</td>
<td>0.70</td>
<td>1.05</td>
<td>1.17</td>
<td>1.54</td>
<td>1.75</td>
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<tr>
<td>XIV</td>
<td>0.38</td>
<td>0.25</td>
<td>1.20</td>
<td>0.65</td>
<td>2.00</td>
<td>1.82</td>
<td>2.45</td>
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<tr>
<td>XV</td>
<td>0.25</td>
<td>0.25</td>
<td>1.07</td>
<td>0.98</td>
<td>1.63</td>
<td>1.50</td>
<td>2.80</td>
</tr>
<tr>
<td>XVIII</td>
<td>0.42</td>
<td>0.24</td>
<td>1.30</td>
<td>1.00</td>
<td>2.00</td>
<td>1.67</td>
<td>2.71</td>
</tr>
<tr>
<td>Average</td>
<td>0.36</td>
<td>0.32</td>
<td>1.12</td>
<td>0.97</td>
<td>1.74</td>
<td>1.54</td>
<td>2.68</td>
</tr>
</tbody>
</table>
Most Economical Rate of Walking.—If a rescue man’s purifier or oxygen begin to fail while he is still a good way from fresh air, he is faced with the question: What is the best speed at which to proceed? He may forfeit his life to an incorrect answer. Unless thoroughly instructed, he will be tempted to make a rush for the base, to get the journey done in the shortest time; he would be risking a great deal by giving way to that temptation. In the case of an apparatus fed with a uniform two litres of oxygen per minute, and where the oxygen is running dangerously low while the purifier is still serviceable, the best speed of retreat is evidently that at which two litres per minute are consumed by the wearer. But in the case of the purifier failing in any class of apparatus while the oxygen reserve is still adequate, or in the instance of a Weg or a Gibbs apparatus (where the oxygen delivery is automatically regulated to the demand), in which the cylinder is nearly run down, the problem takes on a new complexion. The best speed of retreat would then be that at which the required distance may be traversed with the minimum output of CO₂ and the minimum consumption of oxygen. Like a steamer or an airship, a man has a most economical speed at which he goes furthest per litre of oxygen or per pound of food. To ascertain that speed is thus of practical value to those using rescue apparatus, and also (it may be added) to those concerned with the economical movement of infantry.

The data of Table 2 (oxygen consumption during walking) yield the following information on the matter:

"C. G. D.’s" most economical rate, breathing air and walking without burden on a laboratory floor, was four miles per hour, at which speed he moved 99 yards on a litre of oxygen. Walking without burden in grass, the same subject’s most economical rate was three miles per hour, when a litre carried him 82 yards. With all the remaining subjects of Table 2—loaded, as each of them was, with a weight of about 43 lbs. —the most economical speed proved to be three miles per hour when breathing air, while, when breathing oxygen and similarly loaded, that rate was three miles per hour for Subjects I, II and III and four miles per hour for Nos. XIII and XVI. It is apparent that increased difficulty of walking, whether due to the man carrying a load or to lack of smoothness of the path, reduces the most economical speed. Under the conditions obtaining in the mine we judge that rate to be about 2½ miles per hour when travelling a flat road and carrying a rescue apparatus.

PART II.

DEATHS DUE TO RESCUE APPARATUS.

In the following list we give particulars of the 14 deaths that have occurred in British mines through the use of rescue apparatus:

Table 6.

<table>
<thead>
<tr>
<th>Date</th>
<th>Colliery</th>
<th>Probable Cause of Death</th>
<th>Number of Deaths</th>
<th>Apparatus</th>
</tr>
</thead>
<tbody>
<tr>
<td>March, 1908</td>
<td>Hamstead</td>
<td>Heat stroke</td>
<td>1</td>
<td>Weg.</td>
</tr>
<tr>
<td>November, 1911</td>
<td>Polling</td>
<td>Defective apparatus</td>
<td>2</td>
<td>Draeger.</td>
</tr>
<tr>
<td>August, 1912</td>
<td>Cadeby</td>
<td>Removed mouthpiece in poisonous air</td>
<td>1</td>
<td>Draeger.</td>
</tr>
<tr>
<td>November, 1912</td>
<td>Cae Duke</td>
<td>Leaky apparatus</td>
<td>1</td>
<td>Draeger.</td>
</tr>
<tr>
<td>June, 1913</td>
<td>Elswick (disused adit)</td>
<td>Oxygen turned off</td>
<td>1</td>
<td>Draeger.</td>
</tr>
<tr>
<td>November, 1916</td>
<td>Newlilgate</td>
<td>Apparatus improperly adjusted</td>
<td>2</td>
<td>Draeger.</td>
</tr>
<tr>
<td>March, 1917</td>
<td>Durham</td>
<td>Defective apparatus</td>
<td>1</td>
<td>Draeger.</td>
</tr>
<tr>
<td>January, 1918</td>
<td>Poolmore Hall</td>
<td>Apparatus improperly adjusted</td>
<td>1</td>
<td>Proto.</td>
</tr>
<tr>
<td>April, 1919</td>
<td>Newtisdon (Shale Mine)</td>
<td>Leaky apparatus</td>
<td>3</td>
<td>Proto.</td>
</tr>
</tbody>
</table>

We view with apprehension the large proportion of casualties attributed to improperly adjusted and leaky apparatus. The statistics of deaths force upon us the conclusion that insufficient attention has been paid at some centres to the methods of testing and adjustment. Obviously it is not enough for an apparatus...
to be constructed on correct lines; it must be proved serviceable by test before being used. We agree with Lt.-Col. Logan's maxim that every rescue apparatus should be regarded as unsafe until it has been proved otherwise.

The Newliston Mine Accident.—Three men wearing Proto apparatus lost their lives while combating an underground fire in the Newliston Oil-shale Mine on April 18, 1919. Dr. Briggs examined the apparatus used by two of these men, and made a report thereon to the Chief Inspector of Mines, of which the following is a digest. The third body and apparatus have not as yet been recovered. Medical evidence was to the effect that the deaths were due to carbon monoxide poisoning.

While at the mine, it was seen that the unions attaching the flexible inhalation tubes to the bags were slack in both apparatus. In one case the union had been put on "across the thread," and was only caught by two or three threads. On being subsequently tested under water, dangerous leaks were revealed in both apparatus in addition to those at the loose unions. In both cases there was leakage of high-pressure oxygen, which in one instance amounted to 2 litres per minute at a cylinder pressure of 25 atmos. Still more serious were the leakages on the breathing circuits. The bag of one apparatus leaked badly at one end of the large rubber-to-rubber joint, owing to the opening being larger than the clamp intended to close it. It was found impossible to make a secure joint at this place. There was a small leak at the inspiratory valve screw of the same apparatus and a large leak between the rubber and metal portions of the mouthpiece, due to the binding being insufficiently tight. Leakage at the latter place is especially dangerous (see First Report, p. 16), as it is at the mouthpiece that the extreme alternation of pressure occurs. With both apparatus the leaks were such that positive internal pressure could only be obtained by aid of the by-pass, and even then it was quite transitory. A number of other tests were applied, but as they gave negative results they may be disregarded here. The following conclusions were given in the report:

"If the apparatus were used in air fouled by whitendamp and were worn in the state in which they were found by the writer, Brodie's and Laird's deaths were due to poisoning by carbon monoxide drawn in through the leaks in the breathing circuit of the apparatus.

"The leakage of oxygen at the high-pressure taps and joints was not a contributory cause of death; its occurrence in these apparatus, however, suggests one possible reason for the unduly rapid fall in the oxygen pressure which appears to have been a feature with several of the apparatus used by members of the exploring brigade."  

"In the First Report of the Mine Rescue Apparatus Research Committee, 1918 (p. 31), it is recommended that no rescue apparatus should ever be used if poisonous air until it has been tested by immersing it in water with the oxygen turned on and the mouthpiece closed. Had this method been applied in the case in question it is probable that the fatalities would not have occurred."

Certain of the views elicited under cross-examination at the Fatal Accident Inquiry following upon the Newliston accident call for comment:—

(1) The Nose-clip Danger.—In the opinion of the instructor and other members of the brigade, the fatalities resulted from the nose-clips being displaced. These were of the "ratchet" pattern—a variety which is particularly liable to be knocked off, and which on that account should be abandoned. While not wishing to minimise the danger attendant on a defective clip, we think that unless the wearer is already suffering from the effects of CO, CO₂, or want of oxygen, the dropping of a clip, even if a breath or two of foul air is inhaled before it is replaced, will not cause risk of his falling immediately unconscious. Indeed, had the blood on this occasion been free from CO, the effect of a few breaths of the foul air would have been imperceptible. The probability is that, in each of the cases in point, the blood was highly saturated with carbon monoxide drawn in through the holes in the breathing circuit before the man stumbled and knocked off his clip. With the frequent use of the by-pass the inhaled air would contain
large percentage of oxygen, and the wearer of the apparatus would thus be able
to support a higher concentration of CO in the blood than if he had been respiring
normal air contaminated by that gas (see p. 16, First Report); but when the
limit of endurance was reached and he was staggering, the displacement of the
nose-clip and inhalation of air through the nose would result in almost immediate
unconsciousness because of the indrawing of air low in oxygen.

(2) Positive Pressure.—The rescue station superintendent held the opinion that,
even if there were leaks in the circuit, the flow would be outward and not inward,
because of the Proto being a "positive pressure" apparatus. A small puncture in,
say, the Proto bag is much less dangerous than the same-sized puncture in the
purifier of the Meco apparatus, because the resulting leakage in the first instance
will usually be outwards and in the second instance usually inwards; but when the
holes are large or numerous, there is no way of maintaining a continuous positive
pressure in any breathing apparatus; instead of that, the pressure in the circuit
constantly tends to equalise itself with that of the surrounding atmosphere; in
other words, there is outward flow through the leaks on expiration and inward flow
during inspiration, no matter of what type the apparatus may be.

As demonstrating this effect, one of the Newliston apparatus, with the union
on the inspiratory tube set as nearly as possible as it was when the apparatus was
received by Dr. Briggs, was fitted with a special appliance to measure the volume
drawn in through the leak while not interfering with any outward discharge. The
wearer was set to do work on the ergometer at a rate which was known from
experiments to be approximately equivalent to that of climbing a mine incline of
1 in 6 at a speed of 1¼ or 2 miles per hour. The inflow from the outer air averaged
0·6 litres per minute, and heavier exertion would have led to a greater inflow.
There was, on inspiration, a negative pressure of half an inch of water at the point.

(3) The Water Test.—Though admitting the good qualities of this test for
leakage, the superintendent took exception to it on the grounds that it wetted
the apparatus and made it uncomfortable to wear, and that the outer cover of
the Proto bag got full of water during the test. As was pointed out by Mr. H.
Walker during the Inquiry, the last drawback is remedied by providing one or
two small holes at the bottom of the cover through which water may drain
away. A rather more cogent reason against the test as described in the First
Report, p. 31—where it was suggested that, before immersion, the slings and
bag-cover of the Proto should be removed—was that if this test were carried out,
the bag joint would have to be broken and remade in replacing the cover, and that
there was, therefore, no guarantee that the joint was secure when the apparatus
was ready for use. The testing of rescue apparatus for leakage is manifestly of
such importance as to make it advisable to discuss it separately below.

(4) It was argued that the unions may have been loosed by rough usage of
the apparatus between the time of the accident and the examination, or that,
subsequently to the accident, the tubes may have been disconnected and imperfectly
reconnected by some person unknown. This is possible; but the leak at the mouth-
piece and that at one end of the bag-joint cannot be so explained away, and
they were sufficient in themselves to account for the death of one of the men.

Testing Rescue Apparatus for Leakage.—Leaks, even at the high pressure
joints, do not always make a noise; to depend entirely on hearing a leak is not,
therefore, to be recommended. The method of using a glowing cigarette or match-
end is generally more successful in detecting leakage of oxygen from the supply
parts of the apparatus than in spotting leaks on the breathing circuit. It can-
not be too often emphasised that, even with the so-called "positive pressure"
apparatus, a serious leak on the breathing circuit, especially at a place near the
mouth, leads to inflow as well as to outflow of air, and during inflow the hole may
escape detection by the cigarette test. That test also has obvious limitations
underground. To test an apparatus at the pit head by wearing it in a closed
room full of sulphur fumes cannot be recommended for four reasons: (1) The test
is slow and troublesome; (2) it does not reveal leakage from the oxygen supply;
(3) an entry of the fumes into the breathing circuit at a point from which the
air has to flow through the purifier before reaching the mouth may pass undetected, since caustic soda absorbs \( \text{SO}_2 \); and (4) if a leak is discerned, there is no precise indication of its position.

It has been proposed to use a watergauge attached to the breathing circuit as a leakage indicator, the apparatus being inflated and the rate of fall of the gauge observed. The method, however, suffers from the demerits (2) and (4) above, as well as from the objection that a joint has to be remade when the gauge is removed, unless the gauge is applied at the orifice of the rubber mouthpiece.

We know of no test of leakage to equal that in which the apparatus, tightly distended and with the oxygen on, is plunged under water. The water test scrutinises both the breathing circuit and the high-pressure joints: it not only detects leakage, but also shows at once where it occurs. As was illustrated on the occasion of the Wallyford fire (January, 1919), where every apparatus was subjected to it before being taken underground, the water test is readily applied at the pit-head, a collapsible bath being taken out from the rescue station with the rescue apparatus. The fact that every man witnessed the testing of his apparatus on that occasion was responsible, according to the Instructor (Mr. J. Cooper), for increased confidence.

The fact that the test wets the apparatus has been advanced as a serious disadvantage. A slight and transitory discomfort is barely worth mentioning when pitted against the safety of the wearer.

As has been recently observed, it is advisable to shake the connections when under water, as a slack joint may be passably gas-tight in one position and leak badly in another. A suitable way of testing the Proto is, first, to put it under water in an inflated condition, with the belt and bag cover removed—when the connection and tubes can be scrutinised and the rubber bag can be examined for punctures—and, second, to replace the belt and bag cover, and then, with the bag upside down, to immerse the bag-joint to make sure that it is tight. In this way most of the cover is kept dry. As has been pointed out, it is not sufficient that the test be applied with the cover off, for, in replacing the latter, the bag joint has to be remade after testing.

The water test is essentially a pit-head test: it will be only rarely that it can conveniently be employed at an underground base. If a secure method is used of connecting a water gauge to the rubber mouthpiece orifice and also of applying suction, it would form a serviceable alternative to the water test for testing the breathing circuit, though not the high pressure parts.

We repeat, that no rescue apparatus should be used in a poisonous atmosphere unless it has passed a satisfactory leakage test.

**PART III.**

**APPROVAL OF MINE RESCUE APPARATUS.**

If the Home Office agrees to institute a system of testing rescue apparatus it is order that those satisfying the tests may be regarded as "approved apparatus"—and that formed one of the most important recommendations of our First Report—it will be necessary to adopt a definite routine for the examination, so that makers will be aware of the standards of performance that have to be reached. Several of the requirements of apparatus were defined in the First Report, and these will be found to have been incorporated in the following suggested conditions of test:

**Suggested Conditions and Character of Official Test of Two-hour Rescue Apparatus.**

1. The maker of the apparatus, or his agent, shall send to the testing officer two identical models of the apparatus to be tested, along with such cartridge or chemicals (excepting oxygen or liquid air) as will enable the following tests to be carried out. The maker shall also send such additional parts and additional cartridges or chemicals as the officer may request. Should an apparatus fail to comply with the requirements, the two said models will be returned to the maker.

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in the event of an apparatus receiving approval, one model will be retained by the officer on behalf of the Home Office. Along with the apparatus the maker shall also forward to the officer a clear drawing of the apparatus to indicate its manner of working, and a complete schedule of parts of the apparatus stating the material of which each is made, and the name by which it is proposed that the apparatus shall be known.

2. A rescue apparatus shall only be allowed to be used in mines—If (a) it has satisfactorily passed the tests outlined below, and has received the official certificate of approval; (b) it is made in the manner and of the materials specified in the description which is attached to the official certificate of approval; and (c) it be provided prior to use with the kind and amount of consumable charge stipulated in the said description: or if (d) it has been approved for experimental purposes by an inspector designated by the Home Office.

3. In the event of the manufacturer desiring to make an alteration in an apparatus already approved, application shall be made to the Under Secretary of State, Home Office, Whitehall, defining the exact nature of the proposed alteration. The Secretary of State will then decide whether the proposed change is of so fundamental a character as to necessitate complete re-testing in the manner herein prescribed; whether it necessitates re-testing in part only or to a modified extent, or whether the alteration may be permitted without further testing.

4. If more than one manufacturer desire to make a particular apparatus, each manufacturer shall comply with the conditions here set forth, irrespective of any approval previously granted on that apparatus to any other maker.

5. Approval may be cancelled in respect of an apparatus which is found, subsequent to approval, to be made by a manufacturer of inferior materials or involving inferior workmanship.

6. The maker shall be allowed to be represented at the tests of an apparatus or part thereof.

7. In the event of an apparatus, or part thereof, failing to comply with the requirements, a report will, if desired, be furnished to the manufacturer setting forth the cause or causes of failure.

The report on an apparatus which has failed to comply will not be made public by the Home Office.

8. A rescue apparatus shall undergo the following examination and tests:

(a) General Construction and Serviceability.—The apparatus shall be constructed of the best available materials and be of mechanical strength sufficient to withstand the usage it is likely to receive in actual service. The parts shall be arranged with due regard to the comfort of the wearer and shall have been designed on correct mechanical principles. The apparatus shall not unduly impede the wearer when he is walking in a crouching position or when he is crawling. The arrangement shall be such that the parts can easily be tested, inspected and repaired.

In the case of compressed oxygen apparatus, a gauge shall be provided to enable the reserve of oxygen to be read at any time. The gauge shall be within view of the wearer, and, if it is connected to the cylinder by a flexible tube, there shall be a cock or other efficient means of shutting off the gauge and flexible tube from the cylinder. Such apparatus shall have one cylinder only, and the cylinder valve shall be either so constructed that it cannot accidentally be closed, or provided with a suitable locking device serving that purpose. There shall be a by-pass to permit of a free flow of oxygen from the cylinder to the breathing circuit of the apparatus independent of the reducing valve. There shall be a relief valve (preferably operating automatically) on the breathing circuit, and if it be automatic in action, the construction of the apparatus shall be such as will prevent the bag being accidentally squeezed flat.

Unless an apparatus complies with these general requirements, it shall be rejected without further examination.

(b) Purifier Test.—If the material used for absorbing carbon dioxide is contained in a sealed canister or cartridge, the latter shall be so constructed that the absorbent cannot be so disturbed by shanking as to impede the flow of air through it, or to create open passages or short-circuiting within the cartridge.
Unless the design of the cartridge is such as definitely to preclude any set movement of the absorbent, three sealed cartridges will be subjected to shaking or vibration for three minutes and then tested separately by either (1) passing through each of them, in an intermittent flow, air saturated at blood temperature and containing carbon dioxide of a volume and proportion to represent the expiration of an average man walking at 4 miles per hour for a period, in each case, of 2 hours, or (2) by attaching each cartridge to an approved resuscitation apparatus and subjecting it to the endurance test as set forth in (d) below. Measurements of resistance (by water-gauge) and samples of the air discharges from the cartridge will be taken at intervals. The purifiers will be regarded as having satisfied the test if the highest recorded resistance due to the purifier also is under 2 ins. of water column, and if the highest CO₂ proportion in the air passing from the purifier is under 2 per cent.

This test will not be applied to a purifier forming part of a liquid air apparatus in which the supply of fresh air to the wearer is so copious that the greater part of the expired air discharges to waste without passing through the cartridge.

(c) Tests of Expiration and Inspiration Valves.—If the valves on the breathing circuit possess novelty of design or arrangement, tests will be made to ascertain their efficiency. A valve shall not be regarded as satisfactory if its slip in position exceeds 20 per cent. when the volume being respired is 40 litres per minute.

(d) Endurance Test.—This test will be performed four times, namely, twice with each of the models submitted by the manufacturer, and the apparatus will be worn by different persons on each occasion. Persons accustomed to using resuscitation apparatus will be selected to wear the apparatus.

The person wearing the complete apparatus shall walk at a regular rate of 4 miles per hour on the level for a period of 2 hours, with rest intervals not more than 5 minutes each at the expiration of 30, 60, 90 and 105 minutes when samples of air and thermometer and other readings may be taken. Samples and readings shall also be taken at the end of the two-hour period.

In the case of an apparatus dependent on a uniform oxygen delivery, the rate of delivery will be set at 2 litres per minute before the commencement of the test and the rate will again be measured at the end of the test. Before an apparatus is put on, it will be tested for leakage and any leak remedied. An examination for leakage will also be made after the two-hour period. Unless the apparatus derives its oxygen supply from the evaporation of liquid air, only oxygen of at least 98.5 per cent. purity will be used in this and the subsequent tests, and the cylinder will first be washed out with such oxygen before charging.

Samples of air from the inspiratory tube of the breathing circuit will be taken at intervals and analysed forthwith for carbon dioxide and oxygen. The temperature of the inspired air and the cylinder pressure will also be recorded at each interval.

An apparatus shall not be regarded as satisfactory unless (1) it proves itself, each of the four endurance tests, to be able to meet the wearer’s requirements for the full period of 2 hours; (2) the highest CO₂ percentage in the samples taken does not exceed 2 per cent.; (3) the highest temperature of the inspired air is not met than 20°C. (36°F.) in excess of the temperature of the atmosphere at the time the maximum reading was taken; and (4) the highest resistance of the apparatus as a whole (measured immediately at the end of the two-hour period) does not exceed 3 inches of water when the rate of flow is 85 litres per minute.

(e) Training Gallery Test.—This test will be undertaken in anisable air in a suitable gallery. Two men, each equipped with the apparatus, will work two hours in the gallery. The men will be required to undertake a definite programme involving varied exertion for two hours. The programme may include weight lifting, weight carrying, loading a mine tub, tramming, carrying a dummy figure on stretcher, crawling through low narrow openings, and sawing and setting timbers. The test is mainly to determine the degree of security and comfort attainable when wearing the apparatus and when performing some of the common tasks of miners and the nature of the work will be in all cases arranged by the testing officer as he
be deemed by him most suitable to reveal the defects or limitations of the particular apparatus.

9. A nose-clip shall be so constructed, or so attached, as to afford reasonable security against accidental displacement through a chance blow, or through the wearer stumbling. It shall not tend to slip when the nose becomes moist with perspiration.

10. A face mask shall not be approved for use with mine rescue apparatus unless it passes all the tests imposed upon it by the testing officer.

11. Approved rescue apparatus, or parts thereof which have been separately approved (excepting nose clips), shall, before leaving the maker's works, be stamped or otherwise clearly marked with (1) the maker's name and serial number; (2) the inscription "Mine Rescue Apparatus: Approved for Use in Mines in the United Kingdom," and (3) the date of approval. It shall be illegal for a maker to stamp or mark apparatus in this manner unless he has, on his own behalf, obtained approval for the apparatus.

12. The approval of a mine rescue apparatus, or part thereof, has reference only to the question of its safety for use, and takes no cognisance of the legal right of a manufacturer to make the apparatus. The certificate of approval is not to be regarded as equivalent to a licence to manufacture the apparatus or part in question.

PART IV.
MISCELLANEOUS.

Qualifications of Rescue Station Instructor.—General Regulation 144 states: "Every Central Rescue Station shall be placed under the immediate control of a competent person conversant with the use of the appliances." Though the responsibility for operations with rescue apparatus, in common with all other operations at a mine, devolves upon the manager, the rescue station instructor must necessarily be consulted as to the feasibility of any proposed course of action with the apparatus, and as the specialist on such matters, his advice must often be sought and followed. We consider it advisable not only that he should be capable of giving a sound opinion, but also that his views (especially as to the safety or otherwise of rescue operations) should carry weight. To possess the character, knowledge and status desirable in the holder of a position of this responsibility predicates a standard and a good deal beyond a bare acquaintance with the use of the appliances at the station, and, in future, before an instructor is appointed, we think that his qualifications in these respects should be carefully scrutinised.

Cooling the Inspired Air, Proto Apparatus.—All users of the Proto agree that the high temperature attained by the inspired air constitutes a most serious drawback, and, as was shown in the Doncaster Report, other forms of apparatus may develop the same defect when they are used in warm air. On occasion, the hot saturated air produces an insufferable burning of the mouth and throat. The most serviceable method of cooling which we have so far tried is a modification of that of the Doncaster experiments, where a bag containing sodium sulphate (suggested for this purpose by Mr. T. F. Winnill) was placed between the wearer and the inspiratory compartment of the Proto bag. The success of the method was demonstrated at Doncaster, and it has been applied at other rescue stations and in France during the war, the salt being contained either in a third compartment next to the wearer, or in separate small bags lying on top of the caustic. The latter variant was tried at Crumlin in 1917 by Mr. A. T. Winborn and Mr. R. J. Currie, who reported very favourably on it. In one instance, where two Proto men, one with cooling bags in his apparatus and the other without, were pitted against each other in a 2-hours programme of strenuous work, the latter had to stop in one hour owing to excessive heat. The temperature of his inspired air was then found to be 130° F. The first completed the 2-hours task, the temperature of the indrawn air being 87° F. at the end of the period. Other tests gave similar results.

* Second Doncaster Report, p. 79.
† Also see Colliery Guardian, Vol. CXVIII, p. 238.
Hydrated sodium sulphate (Glauber's salt) melts at 92° F., and in melting absorbs a large amount of heat; but extended observation has shown it to be not very suitable for the purpose in view. It has the peculiar property of depositing the anhydrous salt if it be heated above 92° F., as would of course occur if it continued in contact with the purifier after being completely liquefied; and the higher the temperature to which the fused salt is raised, the greater the proportion of anhydrous sulphate precipitated. Thus, a bag of Glauber's salt, raised first to a higher temperature than its melting point and then allowed to cool, is found to contain partly the salt in its original state, partly anhydrous sulphate and partly a saturated solution; and the last two are of limited use as heat absorbers. This action tends to be cumulative, as its impaired cooling power would probably result in the bag attaining a still higher temperature when it was next used, and a further decomposition of the hydrated sulphate would then occur. In place of sodium sulphate, Gilchrist suggested hydrated calcium chloride (CaCl₂6H₂O), which melts at 84° F. and which, as it returns to its original condition on cooling, can be used a number of times. Experiments have also been made on sodium chromate (Na₂Cr₂O₇10H₂O), which liquefies at 74° F.

Calcium chloride, though it has proved an excellent cooling medium, has the disadvantage that, in the event of its containing bag or tube being punctured, a resulting mixing of the chloride with the soda and sodium carbonate of the piping charge leads to a considerable evolution of heat.

If the apparatus is to be worn in hot mines, failure may result from the rise of the wearer's body temperature, caused by the hot bag being insufficiently insulated from the body, rather than from the temperature of the inhaled air. In such circumstances the 3-compartment bag, with the cooling agent in the sealed compartment nearest to the body, affords a most effectual safeguard, though the bag is obtained at the cost of a bag which protrudes awkwardly.

On the other hand, if the problem is to improve the capacity of the Protector apparatus for hard work in places where the temperature of the atmosphere is not uniformly high, attention has then principally to be directed to cooling the purified air; and the ideal situation for the cooling agent is in contact with the regenerators but not in contact with the caustic soda. If the cooling agent in this instance is placed, for example, in a few small bags resting on the soda, its usefulness is diminished by it absorbing heat from the caustic rather than from the air leaving the caustic. Moreover, the small bags are apt to work down into the soda, so that the salt soon melts; and, if of rubber, they run the risk of being punctured and the charge is kneaded or shaken up.

We have tried using a calcium chloride cooler attached to the top of the bag, placed outside it, but all such arrangements are clumsy and unsatisfactory. The best method of applying the cooling salt which we know at present, is to place sealed, round-ended tubes of thin metal, each about 6 ins. long and 1/4 ins. diameter. These are dropped into a special small compartment (A, Fig.

![Fig. 1.—Proto bag with Cooling Compartment.](image)

* Such a tube holds about half a pound of hydrated calcium chloride. For experimental purposes we have used lengths of the inner tube of a bicycle tyre, but the metal tube is preferable as it reduces the chance of puncture to negligible proportions.
through which the regenerated air has to flow on its way to the inspiratory tube of the apparatus. So placed, the risk of puncture is small, and the cooler is kept off the caustic. Any desired number of the tubes can be inserted. Usually, four are found sufficient.

**Oxygen Purity.**—On the whole, the oxygen supplied to rescue stations appears to be much freer from impurity than it was in 1917. Almost invariably at the present time, that obtained at the Edinburgh, Porth, and Doncaster stations contains less than 2 per cent., and generally less than 1.5 per cent., of nitrogen. The position is not so favourable at Newcastle, where the oxygen received often has over 1.5 per cent. impurity, while in September, 1919, the nitrogen-content reached the dangerous level of 8 per cent.

All the more progressive rescue stations have installed analysis apparatus or have arranged for the analyses being carried out by an independent chemist. Oxygen purity is a matter demanding constant watchfulness, and it is evidently impossible to depend on a works' guarantee.

**Prevention of Rusting of Oxygen Cylinders.**—The formation of rust or scale inside the cylinders of rescue apparatus was referred to on p. 25 of the First Report, where we touched upon certain of the risks of rusting. The Proto cylinders are particularly prone to give trouble from rust because of the narrowness and length of the passage from the cylinders to the reducing valve, and of the fact that that passage is all in steel. The danger with double-cylinder apparatus takes three forms: (a) The rust may choke the connection between the cylinders; (b) It may choke the pipe between the cylinder and the reducing valve, and (c) It may be ejected into the reducing valve and cause a stoppage there. In existing apparatus the second of these dangers is almost entirely limited to the Proto apparatus, and there the most likely part of the delivery neck to get choked is the part which is nearest to the cylinders, and, therefore (because of the curved shape of the neck), the most difficult to clean. This part is of narrow bore.

The third of the risks named above is avoided by the use of an effectual filter, placed immediately before the reducing valve. We have alluded to these filters in the First Report, pp. 25 and 26, where we mentioned the fact that in the Meco apparatus the filter has often been found to be absent, or only represented by gauzes having a mesh larger than the openings they were intended to protect. We recently met with a Proto apparatus similarly provided with a gauze which was obviously too coarse, and though in that instance the apparatus had been out of the makers' hands for three years, and the gauze may, therefore, have been changed during that interval, it was evident that it had been fitted in place by some person who did not realise the danger in question.

Since the First Report was written, evidence has accumulated bearing out the risk of the connection between the two Proto cylinders becoming choked by rust. Mr. W. Clifford relates* that during the recovery operations at Norton Colliery, in 1912, a certain pair of cylinders was found more than once to be partially run down when it came to be used; yet immersion in water failed to show any outward leakage. He noticed that the cylinders appeared to fill unusually rapidly at the pump, but that when they were closed and disconnected from the pump, the pressure slowly sank to about half the charging pressure, thus proving the presence in the pipe joining the cylinders of a plug of rust, which only permitted of a tardy equilisation of pressure. He states that since that time he has had several similar occurrences, and points out that the partial choking of the connection pipe is a danger, as the cylinders may be pumped up until the pump gauge shows a pressure of 2,000 pounds, but even then they would not contain a two-hours' supply of oxygen. The inference is clear: the oxygen should be held in one cylinder instead of two. But for the war and the fact that the existing official specifications as to the strength and weight of small cylinders have not yet been modified, this change would doubtless have been introduced already.

* Trans. I. Min. Engs. LVI, p. 269.
The most direct route of attack on the dangers attendant upon rust is an endeavour to prevent its formation. In the last Report we suggested coating the inside of oxygen cylinders, when new and after each annealing, with a varnish of a specified composition, that treatment being the most satisfactory we had then tried. We ventured to give the opinion at that time that experience might eventually point to some other method of protection as being superior to varnishing. Further experiment has, in fact, already led to the discovery of more effectual protective coatings, though none is so simple and easy to apply as varnishing. Certain of the processes named below may be known to the reader in connection with the protection of iron and steel structures of various kinds, but the have not hitherto been considered for preserving oxygen cylinders against corrosion. The present problem is, indeed, not an easy one, owing to high-pressure oxygen especially when damp, being an intensely active chemical agent. The shape of the bottle, with its narrow mouth, enhances the difficulty of treatment and the subsequent examination of the inside surface.

To obtain comparative indications as to the value of certain methods of protecting steel from attack by high-pressure damp oxygen, eight mild steel bars were mounted in a cage and placed within a strong mild steel casing sufficiently large to hold the cage without any of the bars touching the sides of the casing. One of these bars was untreated, but the others had been given protective coatings, or to guard against failure through incorrect application, the bars (with the exception of those varnished and japanned) were obtained from the firms specialising in the methods in question. A pad of wet wool was placed in the casing to maintain the high-pressure atmosphere in a saturated state. Oxygen at a pressure of 80 atm. was then introduced, and the casing kept closed for the weeks. After being withdrawn, the rods were arranged in the following order of merit, the first being the best:

1. 

(1) Tricelised.—Although the surface of the bar had a tinge of rust here and there, the action had been very slight, and the protection proved far and away the best of those tried. The treatment is carried out by the Rustless Iron Co., Keighley, Yorkshire; it consists of first heating the metal in a reducing atmosphere to a temperature not exceeding 900° F. (482° C.), and then subjecting it to the action of superheated steam, with the result that a coating of a magnetic oxide of iron is formed.

2. 

(2) Sherardised.—The result was good. The effect of the damp oxygen had been to form a slight amount of very fine white powder scattered over the surface. This powder seems to have baffled the chemist, and its exact nature is not yet known. Sherardising is carried out by Mr. Sherard Cooper-Coles, of Sunbury-on-Thames, it involves subjecting the metal, at a temperature of about 600° F. (316° C.), to attack of zinc vapour, the surface being in this way zinc-coated. The inventor claims that the zinc forms a zinc-iron alloy at the surface, and the present test when compared with that on a bar given an electrically-deposited zinc surface (see below), goes to support that claim.

3. 

(3) Japanned.—Here, again, the result may be termed satisfactory, though there were a few pimples of rust which had made their appearance through cracks in the "pin-holes" in the japanned surface. A previous trial with japanned iron gave the result superior to this. Black japan consists of asphaltum mixed into a preparation of gum anime dissolved in linseed oil and turpentine; it is applied in a set of thin coats with stoving in between.

4. 

(4) Coslettised and Pigmented.—The rod was provided by the Coslett Co., Birmingham, having been coated by them, after coslettising, with a pigment whose nature was not specified. Local rusting occurred, the rust tending to grow in form of round pimples which easily broke off, and which would be objectionable in an oxygen cylinder. Coslettising consists of coating the steel with iron phosphide by a wet process.

5. 

(5) Varnished.—In the instance under examination, the varnish, though it was not scaled, had allowed rust to break through at places. Though much better...
no protection, varnishing proved decidedly inferior to the above-mentioned methods, and especially to the first two. The varnish consisted of shellac dissolved in methylated spirit, venetian red being added to the solution.

(6) Electrically-deposited Zinc.—This method, which has proved superior in practice to sherardising as a protection against sea water, appears considerably inferior to the latter in the presence of high-pressure oxygen. Besides the deposit of white powder remarked upon in the case of (2), there was a considerable growth of red rust which had broken through the protective covering. The treatment is evidently of little or no service for the purpose in view.

(7) Coslettised.—The process gave very little protection. The same result had previously been arrived at with rods coslettised by Dr. Desch, Glasgow, and kindly sent by him for trial.

(8) Untreated Rod.—There was most marked rusting.

The problem of the protection of oxygen cylinders against corrosion cannot yet be considered as solved, and we put forward these results more by way of a progress report on the matter than as offering a final settlement. The Oxygen Research Committee of the Department of Scientific and Industrial Research, as well as ourselves, continue to devote attention to the problem. A Chesterfield light cylinder (see p. 42) was tricellised and afterwards hydraulically tested. It was found to have suffered no diminution of strength; but although it had received an excellent outer coat of the black oxide, the inner surface left much to be desired. A considerable modification of the method adopted at the works will be needed to treat gas cylinders successfully. As the coating of magnetic oxide is most difficult to remove, care must be taken either to protect the screw at the bottle neck during treatment by screwing in a tube, or, in the case of a new cylinder, to cut the screw after tricellising; otherwise trouble will be encountered when the valve comes to be sweated into place.

Besides the methods discussed above, we have experimented on the action of high-pressure oxygen on the hard enamel coating (virtually a glass) familiar to users of culinary vessels. The protection offered was excellent; but the liability of the covering to crack (especially during the expansion of a bottle when being charged), and the difficulty of obtaining a perfect coat of that kind inside a cylinder, led to the idea being abandoned.

The Drying of Oxygen.—The rusting problem may be attacked from another side: an endeavour may be made to dry the oxygen forced into the cylinders of rescue apparatus. It has been repeatedly observed that the cylinders coming from the various works of the British Oxygen Company are wet, and on some occasions, particularly in the Newcastle and Doncaster districts, to such a degree that water is discharged from a storage cylinder when it is held mouth downwards. The Company tests the cylinders hydraulically, and it is to be regretted that too little care is exercised in clearing the cylinders of water after that test. They should, indeed, be thoroughly dried before again being put into service, and, to avoid disturbing the valve in so doing, the drying may preferably be performed by warming the cylinder while it is in connection with a vacuum pump.

A precautionary measure which can be carried out at a rescue station, and which we strongly recommend, is that of introducing a drier between the oxygen pump and the cylinder being charged by the pump. Even if perfectly dry oxygen were obtainable from the manufacturers, it would often carry water from the pump owing to the common use of a mixture of water and glycerine for lubrication. Fig. 2 illustrates a simple drier, designed by Mr. D. Penman and intended for use with a small oxygen pump. It has been installed for several months at the Edinburgh station, where it gives satisfaction. It was tested hydraulically at 200 atmospheres before being put into use. The case and cover are of mild steel, the joint between the two being made secure by a lead washer. The drying medium, whether coarse caustic soda granules, caustic soda balls (a recent product of Messrs. Crosfield's), or fused calcium chloride lumps, is contained in an inner sheet-metal container. A plug of glass-wool (not cotton-wool) at the discharge side prevents particles of
the drying substance being carried into the cylinder. The bottom portion of the inner case is arranged as a trap for any liquid that may collect. The drying chemical should be changed at regular intervals, which should be shortened if

opening the case, liquid is found within. The drier is provided with two cocks to avoid wasting the compressed oxygen which it holds after a cylinder has been charged.

**The Choking of Reducing Valves by Water.**—The entry of water into the cylinder of a rescue apparatus is not only objectionable from the point of view of corrosion it may set up; if ejected into the reducing valve, it is not unlikely to cause a stoppage. Mr. J. Cooper, then instructor at the Edinburgh station, reported a sudden cessation in the oxygen delivery of a Meco apparatus which was being used by one of a colliery brigade during an underground practice. On returning to the station the apparatus was found to function properly. It was overhauled, but nothing unusual was discovered other than a few drops of water in the reducing valve. A similar occurrence with a Proto apparatus has been recently recorded by Mr. F. P. Mills of Newcastle. We made a series of experiments on the influence of water in the Meco reducing valve. It was found that the mere fact of compressed oxygen in the cylinder being saturated did not lead to choking the reducing valve itself did not contain water. That result was to be expected since the oxygen, though saturated at high pressure, would be very dry at expansion to low pressure.

A stoppage, or partial stoppage, could generally be produced, if the reducing valve contained water, by turning the valve over, and particularly by turning from

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normal position (where the diaphragm is uppermost) to the reverse position. The following is a transcript of the laboratory record of one of these tests:

“A small quantity of water was placed in the reducing valve, the cylinder pressure being 100 atmos. After the oxygen had been flowing normally for a few seconds, the reducing valve was suddenly turned upside down. The flow immediately became less, and continued slowing down until it nearly stopped. Then it came away with a rush, and kept normal for a time. After about two minutes or so, the flow began again to slow down and the above sequence repeated itself. This was done several times with the same results. In no case was complete stoppage obtained.”

The fine oxygen inlet enters the reducing valve at the summit of a cone-shaped projection on which rests the vulcanite valve. So long as the reducing valve is kept in the normal position, any water lodging within the valve box will lie round the base of the conical projection; but when the valve is reversed, the water will run down the cone, which will act as a dripping point. In the latter position, therefore, the water is directed into the oxygen jet, and temporary freezing will probably result, with total or partial stoppage of the flow. After a little time a frozen jet will thaw again and let the gas through “with a rush”; the temperature will then again fall and another stoppage or partial stoppage follow. Freezing at the mouth of the jet, whether of water ejected from the cylinder or of water harking in the reducing valve box and dripping into the jet in the manner stated, is probably due to the cooling influence of rapid evaporation augmented by the Joule-Thomson effect, the ice collecting under the vulcanite and blocking or throttling the inlet passage. We were unable to get a stoppage when the whole reducing valve was immersed in hot water.

If the reducing valve box contain so much water that it is forced through the orifice on the discharge side of the box, it will, of course, lead to a momentary cessation of supply until it has been expelled. The pressure-difference on the two sides of the discharge opening are, however, small, and the cooling effect, therefore, negligible; freezing at that point will thus be a most rare occurrence.

A highly dangerous condition arises when water from the cylinder enters the inlet orifice of a reducing valve, when that opening is already partially choked with rust particles. A sufficient stream of oxygen may emerge through the obstruction so long as it remains dry; but a total and long-continued stoppage may immediately follow upon the entry of water into the duct.

The more completely the results and dangers of allowing water to enter an oxygen cylinder are studied, the greater appears the need for adopting every precaution to prevent it getting in.

**Rescue Apparatus Valves.**—The abolition of the injector in rescue apparatus (a recommendation of our First Report) will render the valves of all such apparatus altogether responsible for the proper direction of the air in the circuit.

A good valve should close tightly, open readily, have little “slip” and, when open, offer little resistance to the flow of air through it. It should also be simple, easily examined and easily changed, and should work equally well when held in any position.

With self-contained apparatus, the effect of slip is rather more important with the exhalation than with the inhalation valve. A small slip at the latter means that a portion of the air last drawn into the lungs gets past the valve, and is re-inhaled on the next breath; that air, however, contains relatively little carbon dioxide. The same slip at the exhalation valve results in the return of the same volume of exhaled air, but this time that volume comes from the end of the previous expiration and contains relatively much carbon dioxide. With apparatus of the respirator type, or the mouthpiece-and-tube appliances described on p. 39, the slip of the expiratory valve is altogether more serious than that of the inspiratory valve; if there should be a slip at the latter, all that happens is the re-inhalation of a

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*If 100 volumes pass through a valve and it let 10 pass back again owing to sluggishness in closing, it is said to have a 10 per cent. slip.*
little CO₂ on the next breath, but if there should be slip or leakage at the forming, some of the poisonous atmosphere passes direct into the lungs at every in-drawn breath.

The apparatus we employed to measure the slip of valves—or, more truly, slip plus leakage—is illustrated by the accompanying figure. A is a pulsatior, designed by Drs. Haldane, Meakins and Priestley for another purpose, and consisting of a rubber concertina which can be made to move a definite distance between stops. It takes the place of the lungs, expiring and inspiring a definite volume per stroke at any desired rate. By setting the stops nearer together or wider apart, shallower or deeper breathing can be simulated. B is a metal mouthpiece, fitted with identical inlet and outlet valves of the kind being tested. Air-tight bags, C and D, are attached on the inlet and outlet sides of the mouthpiece, respectively. On starting a test, C is filled through a dry meter with a known volume of air; its stop-cock is then shut, and the bag connected in the manner shown in the figure. D is completely emptied. The two stop-cocks being now opened, the pulsatior is caused to respire at the rate required for a timed period, during which the number of strokes is counted. Both stop-cocks are then closed, and the volume in the bag ascertained by emptying each through the meter. If the measurements were correctly made and there was no leakage to the outer air during the test, the volume lost by C would have been gained by D. Had the valves been perfect, the volume would be equal to the displacement of the pulsatior, multiplied by the number of double strokes; the extent to which that volume falls short of the later amount evaluates the slip of the pair of valves. The displacement per stroke of the pulsatior with each setting of the stops was carefully ascertained by causing it to respire a counted number of times into a bag fitted with a three-way tap. The tap was worked by hand so that the bellows drew air from outside during inspiration and blew it into the bag during expiration. This “blank” experiment was in each case repeated two or three times. In some of these tests a single-acting piston pump was used instead of the “concertina.”

The mean of several tests of each pair of valves in each of the stated positions is entered in the seventh column of Table 7.

It can be shown that with any single-acting pump (and here the lungs behave as such), if the delivery valve has a slip of S₁ (expressed as a fraction) and the inlet a slip of S₂, the slip, S, of the pair is

\[ S = \frac{S₁ + S₂ - 2S₁S₂}{1 - S₁S₂} \]

In the present case the tests were conducted on pairs of identical valves, or S₁ = S₂ = S, therefore:

\[ S = \frac{2S}{1 + S} \]

Values for S having been determined by experiment, those for S were computed from this formula; they are to be found in the eighth column, Table 7. When S is not more than 0.03 or 0.09 (8 or 9 per cent.), it is close enough for practical purposes to take S = \( \frac{S}{2} \), but larger slips must be calculated from the formula stated.

To compare the resistance of passage of valves, it is necessary to select some rate of flow at which the resistance can in every case be measured. In common with the Anti-Gas Department of the Ministry of Munitions, the standard of 3 c.f.t. (85 litres) per minute was selected for the purpose. That rate will be realised at the middle of an expiration by a person breathing 30 to 35 litres of air per minute.

Of the valves named in the table below, the mica valve is too well known to need illustration. The Thiry valve, first described in 1865, is that used in the Tissot apparatus. It is a clack of thin brass, with a brass seat. It is hinged at the top and is set at 45 degrees to the axis of the tube. Fig. 4 shows two such valves in a Tissot mouthpiece. When the head is in its normal position or turned to the left, the weight of a valve assists it to close, and in those positions the slip is small. When the head is turned to the right, the weight tends to keep the valve open and the slip is large; while if the wearer of the apparatus is facing down, the slip is...
Fig. 3.—Apparatus for ascertaining Slip of Valves.
Fig. 5.—Split-tube Valve.

Fig. 6.—Rosling Valve, shut and open.
the table shows, has an intermediate value. Notwithstanding the narrowness of the tube in which it works, its wide passage-way when open, taken in conjunction with the fact that it allows of almost a straight-line flow along the tube, reduces the resistance of this valve to an unusually low figure.

The rubber disc valve was one taken from an army box respirator where it act ed as inlet. For test purposes it was placed in a metal case attached to a 1-inch tube. The valve is a disc of thin rubber, pinned down at its centre to a grid having six openings through it. Though not particularly tight, its behaviour is not so affected by its position as are those of the mica and Thiry valves. A similar, though smaller, valve has been tried for the Peg apparatus.

The so-called split tube valve (Fig. 5) was made by us in the hope of getting a reasonably slipless valve permitting of a straight-line flow through it. Such a valve could have been mounted in a tube but little larger in diameter than that of the rest of the circuit. It failed, however, owing to its high resistance.

The Rosling square-rubber valve (Fig. 6) is the invention of Lieut. Rosling of the Anti-Gas Department, and was adopted for box respirators by that Department towards the end of the war. In the larger size made for us by the Isleworth Rubber Company, it comes nearer to the ideal than any we have examined. Its slip is very small, its resistance is low, and it is a matter of indifference which way up it may be. The experience of this valve gained by the Anti-Gas Department testifies to its durability in service. The only drawback to its application to rescue apparatus—and it is not a specially serious one—is that it requires to be mounted in a valve-box of diameter considerably larger than that of the tubing leading to and from it.

The last valve on the list (the Mueller valve), though inapplicable to rescue apparatus, is useful in respiration experiments if the subject is stationary, and it has been shown to give satisfactory results for that purpose. The diagram (Fig. 7) is of a glass Mueller valve used by us, and of a size suitable for heavy breathing. The inflow to the valve is by the glass tube A, which dips about half-an-inch below the surface of the water in the jar. The water prevents any return of air up A, but nevertheless there is a small rise of liquid in that tube due to the resistance of

![Tissot Mouthpiece](image)

**Fig. 4.**—Tissot Mouthpiece.
the companion valve when the latter is passing the air, and the volume of water raised in the tube evaluates the slip. Of those tested, the Mueller is the only valve whose percentage slip increases with the volume delivered.

**Table 7.**

*Slip and Resistance of Various Valves.*

<table>
<thead>
<tr>
<th>Type of Valve</th>
<th>Diameter of Valve</th>
<th>Diameter of Tube Leading to Valve</th>
<th>Position of Valve</th>
<th>Leaks in, per minute</th>
<th>No. of Breaths per minute</th>
<th>Percentage Slip of Valves (measured).</th>
<th>Percentage Slip of Valve (calculated).</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mica disc, Douglas, Respiratory Apparatus</td>
<td>1.1</td>
<td>1.0</td>
<td>Right way up</td>
<td>43.8</td>
<td>20</td>
<td>5.6</td>
<td>2.8</td>
<td>Weight of valve helps close it.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>On side</td>
<td>43.8</td>
<td>21</td>
<td>8.2</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Do.</td>
<td>10.0</td>
<td>9</td>
<td>9.8</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Do.</td>
<td>12.5</td>
<td>6</td>
<td>9.7</td>
<td>8.4</td>
<td>The valve was four have jammed so it could not close.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Up side down</td>
<td>50.0</td>
<td>22</td>
<td>24.0</td>
<td>13.6</td>
<td>The valve falls from its seat.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Do.</td>
<td>8.8</td>
<td>4</td>
<td>63.6</td>
<td>46.0</td>
<td></td>
</tr>
<tr>
<td>Mica disc, (Douglas) Seat, 1.0 with spring.</td>
<td>1.1</td>
<td>1.0</td>
<td>Right way up</td>
<td>43.8</td>
<td>20</td>
<td>8.0</td>
<td>4.1</td>
<td>The same valve as fitted with a light trol spring.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>On side</td>
<td>49.8</td>
<td>20</td>
<td>6.0</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Do.</td>
<td>11.0</td>
<td>5</td>
<td>15.8</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Up side down</td>
<td>35.0</td>
<td>18</td>
<td>10.0</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>Mica disc, Proto Apparatus</td>
<td>0.75</td>
<td>1.0</td>
<td>Right way up</td>
<td>34.0</td>
<td>12</td>
<td>1.75</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reversed</td>
<td>34.0</td>
<td>12</td>
<td>23.0</td>
<td>14.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>On side</td>
<td>34.0</td>
<td>12</td>
<td>12.5</td>
<td>6.6</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 7.—Mueller Water Valve.**
SLIP AND RESISTANCE OF VARIOUS VALVES.

<table>
<thead>
<tr>
<th>Type of Valve</th>
<th>Diameter of Valve.</th>
<th>Diameter of Table leading to Valve</th>
<th>Position of Valve.</th>
<th>Effect of Air Breathed per minute</th>
<th>No. of Breaths per minute</th>
<th>Percentage Slip per pair of Valves (measured)</th>
<th>Percentage Slip per Valve (calculated)</th>
<th>Resistance per Valve to passage of 5 c. ft. per minute</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thiry clock.</td>
<td>0.8 Ins.</td>
<td>0.7 Ins.</td>
<td>Right way up.</td>
<td>40.0</td>
<td>20</td>
<td>6.0</td>
<td>3.1</td>
<td></td>
<td>Ins. of Water.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Do.</td>
<td>22.5</td>
<td>9</td>
<td>9.0</td>
<td>4.7</td>
<td>0.25</td>
<td>Weight of valve has no influence.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wearer facing downwards.</td>
<td>12.0</td>
<td>6</td>
<td>37.0</td>
<td>22.7</td>
<td></td>
<td>Weight tends to keep valve open.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Do.</td>
<td>44.5</td>
<td>21</td>
<td>17.0</td>
<td>9.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wearer lying on his side.</td>
<td>45.0</td>
<td>21</td>
<td>53.8</td>
<td>36.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubber disc.</td>
<td>1.5</td>
<td>1.0</td>
<td>Right way up.</td>
<td>51.0</td>
<td>21</td>
<td>16.0</td>
<td>8.7</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>On side</td>
<td>47.7</td>
<td>22</td>
<td>16.8</td>
<td>9.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upside down.</td>
<td>41.8</td>
<td>20</td>
<td>26.1</td>
<td>15.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Split tube.</td>
<td>1.0</td>
<td>0.9</td>
<td>Pointing up.</td>
<td>44.0</td>
<td>15</td>
<td>7.8</td>
<td>4.1</td>
<td>3.65</td>
<td>Owing to high resistance not tested further.</td>
</tr>
<tr>
<td>Rising square (small).</td>
<td>1.25</td>
<td>0.66</td>
<td>Upright</td>
<td>37.6</td>
<td>18</td>
<td>4.0</td>
<td>2.0</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>On side</td>
<td>26.2</td>
<td>11</td>
<td>10.2</td>
<td>5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rising square (large).</td>
<td>0.85</td>
<td>1.5</td>
<td>Upright</td>
<td>27.7</td>
<td>17</td>
<td>2.5</td>
<td>1.25</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>On side</td>
<td>44.5</td>
<td>20</td>
<td>2.0</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upside down.</td>
<td>25.0</td>
<td>12</td>
<td>2.2</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mueller water.</td>
<td>1.1</td>
<td>1.1</td>
<td>Normal</td>
<td>26.2</td>
<td>12</td>
<td>3.0</td>
<td>1.5</td>
<td>1.0</td>
<td>Tube dipping 0.6 in. under surface of water.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Do.</td>
<td>65.7</td>
<td>30</td>
<td>5.5</td>
<td>2.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

When working the proper way up, when the valve's weight helps it to close, the mica valve is thoroughly efficient and its slip is negligible; but if called upon to function upside down, in the manner of the exhalation valve of the Proto apparatus, the slip (as the Table shows) may be serious. It is useless to cut down dead-space if one of the valves may let back a large part of the volume forced through it by the lungs. The effect of re-breathing expired air is to stimulate the respiration (see p. 9): thus, the lungs automatically do their best to close a refractory valve; but should the CO₂-absorption be imperfect, slip becomes a serious matter and may contribute largely to the distress of the wearer, and, in a more extreme case, to his collapse. The results set forth in the table reveal a still more serious state of affairs when the large mica valve of the Douglas respiratory apparatus is resting on its side. Now and then, as shown in the second and third lines of the Table, the slip in that position may not be excessive; but as likely as not the valve may get caught between two of the wires of the cage in which it is usually mounted (see the fourth and fifth lines), and then it is virtually out of action. Though we have no evidence of the mica valve giving trouble through sticking in existing apparatus, and although the Douglas appliance was not meant to be used on its side or upside down, the examples show that there may be risk with mica valves unless they are carefully made.

The mica valve of the first section of the Table was fitted with a light spring to assist it in closing. This addition brought about an improvement in regard to slip in the inverted position, and reduced, to some extent, the chance of jamming when the disc was working on its side. These advantages were secured, however;
at the expense of greater complication and resistance, and it doubtful if modification will commend itself to many.

As might be expected, the tests of valves indicate that the percentage slip with valve in any given position is less with hard than with quiet breathing. There is a fortunate one.

**Nose Clips.**—The problem of devising a nose clip which will provide reassurance against accidental displacement has occupied considerable attention in the last few months. A pamphlet was issued by the Research Department of the British Gas and Electric Light Company in 1919, in which there were illustrated three types of nose clip claiming increased security. The variety of screw clip shown in Fig. 16, and adopted for the Briggs apparatus, is an improvement on a clip described in that pamphlet. Figs. 8 and 9 are reproduced from the pamphlet, and illustrate respective spring clips which have given satisfaction at the Swansea Rescue Stations, and a German screw clip similar in type but heavier and less secure. Thanks to the Superintendents of the Swansea and Crumlin rescue stations for attention to these types. In each of these latter varieties the bow of the nose passes loosely round the metal portion of the mouthpiece. In that of Figs. 8 and 9 a piece of elastic draws the two legs of the clip together. Mr. G. L. Broo also devised a spring clip similar in principle to that of Fig. 8, but all of some variation in the distance between the centre of the pads and the mouthpiece, in this way providing for differences in the length of the nose.* If a form of clip be adopted where the bow encircles the metal part of the mouthpiece, it will be advisable to use a mouthpiece attachment similar to that of Fig. 16, which practically precludes the possibility of the mouth falling out, for, with nose clips of this character, the removal of the mouthpiece entails the displacement of the clip. Another variety of spring clip, possessing a high degree of security, has been evolved by Mr. Hopwood of Altofts. A slightly modified form is shown in Fig. 10, where it will be seen that the clip can be adjusted vertically by slipping it along a leather band. The also prevents the clip being knocked off.

Providing that it is held securely, the screw type of clip has the advantage of greater comfort. It is worth observing that an uncomfortable clip is dangerous in that, during a prolonged spell of work with the apparatus, the pressure on the nose becomes almost intolerable, and the temptation to take off the clip while it is most difficult to resist.

**Face Masks.**—During 1918, the Anti-Gas Department (Ministry of Munitions) devoted considerable attention to face masks in connection with box respirators in order to see if a sufficiently tight joint could be secured to allow of the clip being dispensed with, and masks were evolved by the Department incoining certain novelties in construction and material. Late in the year, Lt. Raper and Major Lambert kindly described to us the course of the experiment and suggested a union of forces to attack this and kindred problems.

We tested two army masks known as the American “Akron Tissot” and British “Tissot” mask. They endeavour to make a gas-tight seal along certain parts of the same circuit of the face as the old-fashioned rescue apparatus and, by attaching, to still greater flexibility of the material from which they are constructed, and to a more exact regard to the facial contour, they certainly a greater tightness at the face joint than did the helmet. At the same time, the results obtained (as will be shortly seen) indicate a degree of security in that of the mouthpiece and nose clip. This, together with the further data of increased dead space, is sufficient to condemn these masks.

A simple outfit for testing masks consists of a cubical box with windows, door, and an opening in the bottom through which the wearer of the mask thrusts his head. A curtain of cloth, or wash-leather, round the bottom can be tucked round the wearer’s neck, or buttoned under his coat, to prevent the gas escaping too rapidly. An absolutely irrespirable atmosphere is in the box by blowing in a little SO₂, from a syphon. The box is hung from the ceiling, so as not unduly to impede the man’s movements, and an ergometer (p. 54) placed under the box makes it easily possible

Fig. 8.—Spring Nose-clip used at Swansea.

Fig. 9.—German form of Screw Nose-clip.

Fig. 10.—Hopwood's Spring Nose-clip.
him hard work (and so promote heavy breathing) while he wears the mask. Inhalation and exhalation tubes passing out of the box carry air to and from the mask. Resistance to breathing may be introduced by throttling these tubes, and its amount indicated by water gauges. Where so much depends on the shape of the face, it is evident that a mask should be tried on several persons, and that extremes of facial cast should be sought rather than avoided.

The clean shaven man presents obvious advantages when dealing with face masks; no matter how good the mask may be, it does not make a secure fit on a bearded or unshaven face, and a long moustache is also undesirable. These are limitations from which the mouthpiece is free.

The American and British Tissot masks were tried on six persons, mostly clean-shaven. The former mask proved the better. It was tight in all cases when the subject did no work, even with resistances such as ±8 ins. of water. The mask lifted off the face when expiring against resistance, and allowed air to escape round it; but, when the subject was at rest, it closed back, valve-fashion, at the end of expiration and made a tight joint. With the majority, the American mask was tight when the subject did work on the ergometer, though one man was distressed by heat; but in certain cases, the slight tugging of the connecting tubes due to the short, sharp movements of the head while working, led to gas being drawn in, even with relatively low resistance like ±2 ins. of water. It became evident that the tubes leading to a face mask must be flexible in the highest degree, or that they must be arranged as in the Weg apparatus (see First Report, p. 10).

The British Tissot mask was tested on five persons. It was found to let in gas with resistances exceeding ±3 ins. of water when the men were resting, and was, therefore, not tried further.

A few experiments were made with the American mask to illustrate the effect of dead-space. By withdrawing air-samples, it was found that, even after inspiration, an appreciable proportion (usually about 0·4 per cent.) of CO₂ remained in the mask, representing a part of the last expiration not swilled out by the inflowing fresh air. As was to be expected, the dead-space held, after expiration, with different subjects and different degrees of exertion, from 3·3 to 5·9 per cent. of CO₂. When the volume of air drawn in per minute was metered, first using the mouthpiece and then using the mask, it was found that the CO₂ in the dead-space of the latter caused an average increase of 16 per cent. in the lung ventilation with subjects doing 5,000 ft.-lbs. of work per minute.

Though our experience of face masks down to the present has not been specially promising, it cannot be denied that a thoroughly secure mask (if such is within the bounds of possibility) would be a valuable adjunct to rescue apparatus. It would allow of the user speaking to his companions without risk; it would enable a telephone connection to be maintained between the leader of a party and the base; it would also permit of breathing through nose and mouth, and do away with the noseclip, besides being probably more comfortable than the mouthpiece.

Useful work on masks is proceeding at the Altofts and Wemyss rescue stations, and at the latter the men have been instructed for a considerable time in the use of the telephone, in which the transmitter is attached to the front of the leader's mask, while his receiver is strapped to one ear. The second in command also has a transmitter fitted to his mask and carries a receiver in his pocket. Should the leader collapse during work, the second man can quickly connect himself to the battery box and thus to the base. Without doubt, such a manner of communication is preferable to signalling, and ready means of communication has a highly beneficial effect on morale; yet all such considerations must remain subservient to the question of security of the mask. The fact remains that we have yet to find a mask which will adapt itself to all faces (leaving bearded ones out of account) and which will make a thoroughly tight joint in the circumstances attending actual service with rescue apparatus. In our own attempt to solve the problem, we have worked upon a line suggested, and to some extent developed, by the Anti-Gas Department, the joint against the face being made by a shaped ring of rubber sponge. Owing to the difficulty of getting supplies, we have, however, not progressed sufficiently far with
this type of mask to enable a conclusion to be reached; but we hope to deal with
the matter in the Third Report.

We have here considered the face mask as a possible substitute for the mouthpiece
and not as an addition to the mouthpiece. The army box respirator, as is well
known, includes both mask and mouthpiece. Such a combination may occasionally
be useful with rescue apparatus. For example, when it became evident at the
Front that the Germans were using lachrymatory charges in mining operations,
the exploration of galleries after a "blow" was often carried out with Salve
apparatus fitted with the mask, mouthpiece and noseclip of the box respirator.*

Flow Gauge for Proto Apparatus.—Fig. 11 is a section of a flow gauge designed
for use with the Proto apparatus. The mode of action is the same as that described

![Flow Meter for Proto Apparatus](image)

on p. 45 in connection with the Briggs apparatus, and like the latter, it is intended
to indicate continually the flow of oxygen from the reducing valve. The position
of the device when attached to the apparatus is shown by the photograph, Fig. 11
where it will be seen that the small circular gauge, while lying close to the wearer's
body, is easily within his view. Prior to attaching the device, the small orifice on
the outflow side of the reducing valve is removed, since the resistance of the plug of cotton
wool takes the place of that of the orifice. The principle and mode of adjustment
of the device is described on p. 45. Though this type of meter was first used with
the Proto apparatus in the manner here shown, it does not lend itself so well
that apparatus as to Dr. Briggs', since the discharge of the by-pass is in the
former case on the in-flow side of the resistance, while in the latter apparatus
is arranged to be on the out-flow side.

Warning against the use of the Army Box-Respirator, Eeds Smoke and Gas
Helmets, and similar Appliances for Mining Purposes.†

There is an erroneous belief, especially among demobilised men returning to the
mines, that the army box-respirator, which has proved so excellent a protection against poison gas, would safeguard a man equally well if he were
attempting to penetrate a noxious atmosphere underground. An appliance known
as the Eeds Helmet is being advertised in the mining technical papers, and as it
is recommended by the makers for use in mines, it is necessary in the interests

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† This warning, in substantially the same terms, was issued to the technical press under
26th May, 1919.
Fig. 12.—The Flow Meter in position, Proto Apparatus.
safety to warn mine managers and superintendents of rescue stations that this appliance, like the army respirator, is inapplicable for mining purposes.

In the Eeds appliances, the air is intended to be drawn through a sponge filter which is dipped with water or other solution. Apart from the fact that the high resistance of the filter—much increased by saliva—makes it impossible to carry out physical work while using the Eeds helmet, such an apparatus is wrong in principle if intended for service underground. The main risk in attacking a mine fire, or in penetrating workings after an explosion, is due to carbon monoxide. A second risk, which is seldom of importance at the surface, but which cannot be disregarded in mines, is that an atmosphere may be entered which contains an insufficient amount of oxygen to support life.

Neither the army respirator nor the Eeds appliances give the least security against either of these dangers, and if they be used in mines, the result may be fatal to those wearing them. The army respirator, and, to an inferior degree, the Eeds helmet, will stop smoke; for that reason they would give a person ignorant of the real danger a feeling of security when entering smoky air, and thus would add to the probability of his being overcome.

This type of breathing appliance, therefore, cannot be looked upon as a substitute for self-contained rescue apparatus.

The Smoke Helmet and other Hose-pipe Apparatus.—Limited in scope though the smoke helmet must necessarily be, it has proved itself of service on several occasions, as, for example, in fighting fires after the Senghenydd explosion, 1913, and at the Ashington Colliery in the same year. In the latter case the helmet allowed men to use water-hoses on the fire and enabled them to open separation doors in foul air.

The possibility of using compressed air (when available) as a means of feeding helmets has received little attention; yet on one occasion, namely, in the attack on a large timber fire in the Homestake Mine, South Dakota, U.S.A., in 1907, the method proved successful. In that instance those at work with the water-jets were provided with leather helmets which received air from a compressed air main through small-bore hoses.

The ordinary smoke helmet, of which there are large numbers at rescue stations and mines, is a modification of the diver's apparatus; like the latter, it completely covers the head of the wearer, and the imitation is in many cases carried so far that a blow-off valve is provided on the helmet when the loose joint round the shoulders makes that valve altogether superfluous.

The smoke-helmet in its usual form has the following special drawbacks and dangers:—

1. The flexible hose is vulnerable; it may be cut by a tub-wheel or by a falling stone; a heavier fall, though it may not block the road, may flatten the pipe, or hold it and so trap the helmet-man.

2. A fall completely blocking the road between the fire and the base spells disaster, as the helmet-man is unable to use any other way of escape, should one exist.

3. The management of the hose by the helmet-man is not easy, owing to its weight and cumbrous character; these features are such as to limit the range, under the conditions usually obtaining in the mine, to about 50 yards from fresh air. If the man is carrying tools or material, he is still further incommoded by the tube, and the practicable range is still further reduced.

4. In such work as building an earth stopping, where tubes have to be run in, the tube becomes a hopeless encumbrance, and the risk of it being cut is much increased.

5. Rapid escape is difficult; if the helmet-man tries to get back to fresh air dragging the pipe behind him instead of coiling it up as he comes, there is a

+ Engineering and Mining Journal (New York), March 28, 1908.
considerable chance of the hose getting caught. Again, there is the possibility that case of him returning on the wrong side of a line of centre-props.

(6) The hissing of air entering the helmet may prevent the wearer hearing a warning noise given by a roof under movement.

(7) Vision is limited: with some helmets extremely so; and it is thus difficult for the wearer to make a proper inspection of the roof.

(8) Two persons are required for each smoke helmet as against one with an self-contained apparatus.

The first five of these disadvantages are inseparable from the use of a hose, as it cannot be removed except by giving up this type of apparatus; but it seems to us probable that the last three could be avoided by substituting a mouthpiece attachment for the helmet, and by causing the wearer to draw his air supply through the pipe instead of having it forced to him by a bellows or mechanical blower. Although the modification introduces other demerits, namely, negative pressure, a more limited range of exertion and reduced cooling of the face on the head—drawbacks which we have no desire to minimise—the proposal proves feasible. It really amounts to the revival of the oldest form of breathing apparatus intended for use in mines, for a hose and mouthpiece appliance (with inhalation and exhalation valves) was described in the Universal Magazine of 1752.

No difficulty will be found in drawing air through a mouthpiece and hose, provided no work is being attempted. The lungs are quite capable of sucking seven to ten litres of air through a 3 in. bore tube 30 or 50 yards (and even more) in length, the expired products being discharged direct to the atmosphere; but when exertion is involved and the volume needed increases perhaps six-fold, it becomes physically impossible to obtain the air by drawing it directly from the tube. While the lungs are powerful enough to maintain a flow of, say, 40 litres per minute along such a tube, when that flow is uniform, the lungs are not sufficiently strong to induce a sufficient volume to pass in the intermittent or spasmodic manner which is their natural way of moving air. Evidently, then, if the plain mouthpiece and hose appliance is going to be of practical use, it is necessary to introduce between the lungs and the tube something having the function of the air-vessel of a ram pump, that is to say, that of converting a pulsating into almost a uniform flow.

Before describing the means adopted to change the manner of flow in the hose it is advisable at this point to interpolate an account of certain experiments made on the flow of air through a 3/4 in. bore smoke-helmet tube 90 ft. long. The purpose of the experiments was to ascertain the relation between the volume of air carried by the tube and the pressure required to create the flow, both when the delivery was steady and when it was fluctuating. The results allowed of calculations being made on the power expended in the two cases in drawing a given quantity of air per minute through the pipe. The results may be of use, we think, to those dealing with compressed air transmission, as well as in their relation to the smoke helmet problem. Air was caused to flow through the tube from a closed tank, 3 ft. 2 ft. 6 ins. by 1 ft. 6 ins., from which it was displaced by water. The rate of the water surface, as indicated on a gauge glass, determined the number of cubic feet of air passing along the tube per minute. In the experiments of pulsating delivery, a device operated by a pendulum was connected to the pump. The air was then released in gusts, with pauses in between, thus closely simulating the action of the lungs. In the cases of intermittent flow, it was sought to obtain the maximum water-gauge readings so as to get the "peak" values of the resistance offered by the pipe, and means were used to prevent the readings being affected by the momentum of the water in the manometer.

It is known that when air moves with a uniform speed along a large conduit, e.g., a smooth-walled gallery, the resistance to passage is very nearly proportionate to the square of the volume; it has also been shown that when the flow is placed through a medium such as cotton wool packed into a tube, or an empty "waste" underground, the resistance is approximately proportional directly to the volume. In the case of a small pipe, the air-stream will neither be so free from obstruction as in the first of these cases nor so baffled as in the second. It was, therefore, to be expected that, with the hose, the index of the formula \( k = \) would prove to be somewhere between 1 and 2, and that the more the hindrances...
Fig. 13.—Haldane's Equalizing Arrangement and Air Tube.
to the flow the nearer \( n \) would approach unity. Such indeed has been the conclusion of previous experimenters. We ascertained the laws of flow for the hose in question to be as follows:

(a) Uniform flow—tube uncoiled: \( h = 0.87 \, q^{1/3} \).
(b) Uniform flow—tube coiled up in 20 ins. diameter turns: \( h = 1.2 \, q^{1/3} \).
(c) Pulsating flow—18 breaths per minute—tube uncoiled: \( H = 3.65 \, q^{1/3} \).
(d) Pulsating flow—18 breaths per minute—tube coiled up in 20 ins. turns:
\[ H = 3.8 \, q^{1/3} \]

Where: \( h \) is the resistance measured in inches of water;
\( H \) is the maximum resistance in inches of water;
\( q \) is the volume of air delivered per minute in cubic feet.

The first two of these results indicate that coiling up the tube introduces a considerable change in the nature of flow, the lower index of (b) showing that the air is meeting with hindrance through rebound and eddying. The same degree of difference is not noticeable between (c) and (d); here the jerky discharge is the dominating factor, and the interference to simple "stream-line" flow, which apparently results from the pulsating discharge, is only slightly enhanced by coiling the tube.

The bearing of these results can perhaps best be realised by considering concrete cases. If a man is standing still and drawing air direct from the 30-yard hose at the rate of 10 litres (0.35 c. ft.) per minute, the maximum resistance his lungs will have to overcome will be equivalent to 0.9 in. water when the tube is uncoiled [eqn. (c)], and 1.0 in. water when it is coiled [eqn. (d)], and in either instance the effort will be well within his power. But should he try, without an equilizing device in connection with the tube, to undertake physical work requiring a respiratory supply of 50 litres (1.77 c. ft.) per minute, his lungs would need to exercise suction equivalent to 7.9 and 8.0 ins. water in the respective cases, and he would find it impossible to cope with such a drag for many minutes. Yet if it were feasible to introduce an equilizer to cause the air to flow in a steady stream along the tube, 50 litres per minute could be obtained at a water-gauge reading of 2.2 ins. in condition (a) or 2.6 ins. in condition (b).

The difference between a steady and a pulsating flow is still more strikingly illustrated when we come to consider the work done against resistance in drawing a given volume (say, 50 litres per minute) through the tube in each instance. To make such a comparison we shall assume that the rate of intake of air to the lungs during a breath follows the simple harmonic law; that the rate is a maximum at the middle point of the breath, and that a breath is succeeded by a pause of equal length. Such a mechanical precision of inflow—though almost exactly true in the case of an air compressor—is not, of course, followed by the lungs; but the assumption is sufficiently close for the present purpose. Taking the straight pipe without equilizer, and a delivery of 50 litres per minute, and making use of the experimental results, it can be shown that at the middle of the breath, when both speed of flow and resistance are maxima, the lungs are required to do work at the momentary rate of 230 ft.-lbs. per minute. It also appears that to maintain this intermittent delivery, the power expenditure per minute is 54 ft.-lbs. Had the flow been a steady one, the expenditure would have been only 20 ft.-lbs. Hence the pulsatory nature of the delivery increases the power spent in overcoming pipe resistance in this instance in the proportion of 2.7 to 1, while the peak load is 11.5 times the load to be borne when the flow is continuous.

The two forms of equilizers shown in the figures, while not able altogether to steady the flow, go sufficiently far in that direction to make physical exertion much more supportable while wearing the apparatus.

The original form of the arrangement, illustrated by Fig. 13, was devised in 1914 by Dr. Haldane for use in the turrets of battleships if the air became foul by gases from the guns, and for use in smoke or foul air in other parts of the ships. It is made by Messrs. Siebe, Gorman & Co., and was demonstrated at a meeting of the Institution of Mining Engineers in 1915. In this device the corrugated rubber tubing between the mouthpiece and the hose collapses in the manner of a concertina
during inspiration, while during expiration it elongates again and so fills itself with air. For use in mines, wider collapsible tubing was introduced so as to allow of the being done at long distances if necessary; even at a distance of 200 yards sufficient air can be obtained; but in ordinary practice the apparatus is only used for work at shorter distances, as in gob-fire operations or in exploring cavities and other places filled with irreparable gas. At first saliva caused trouble in the collapsible tube, and to avoid this, the saliva trap was introduced, as shown, and afterward the spear expiratory valve was applied in the same manner as that of Fig. 14.

In the latter appliance, designed independently in Edinburgh, the wearer carries on his back a bellows-shaped bag which is connected by a T-piece to the pipe feeding the mouthpiece. The bag is constructed of balloon fabric mounted on strips of steel which are bent round the sharp upper angle of the bellows and thus form the frame of both the back and the front of the bag. These strips always tend to open and thus to keep the bag distended. Their action is further assisted by a coil of spring inside the bag. When the wearer exhales, the bag, which had been partially flattened during the last inspiration, recovers itself, and in so doing draws in through the hose. On the next breath air is taken both from the bag and the pipe. The effect of the bag is thus to maintain a flow in the pipe during both strokes of the lungs, and so to smooth down the peak loads whose adverse influence has been discussed above. The mouthpiece has a Rosling inspiratory valve and a spear expiratory valve, and the saliva discharges through the latter. The spear valve is protected by a metal guard.

The Electric Head Lamp.—The use of the miner’s electric head-and-belt lamp has spread enormously during the last few years in the United States and Canada, where it is said that 150,000 are in use. Certain of these lamps, e.g., the Edison, Hirsch, Wico, Concordia and Pioneer, were approved by the U.S. Bureau of Mines for use in gassy mines after having been tested for safety, strength and serviceability.* The majority of the gassy mines of Pennsylvania (bituminous district), for example, are equipped with Edison lamps. It speaks well for their security that during 1918, for the first time in the history of that field, twelve months went without a single man being killed from an explosion of gas or dust in the bituminous district, the output of the area for the year being about 200 million tons.†

In Great Britain, it is natural that Scotland should lead in experimenting with the head lamp, owing to the prevalence in the naked-light mines of that coast of the small spout-lamp which is carried on the cap. Excellent electric lamps of this kind (made at the mine) were in daily use ten years ago at the Dalmeny oil-shale mine; they were much liked, but had eventually to be withdrawn as they were not approved safety-lamps.‡ Credit must be accorded to Draeger for introducing the application of a head lamp to rescue apparatus.

Believing that the electric head-lamp had valuable features for rescue work, he obtained one from the United States, and put it into service at the Edinburgh rescue station 18 months ago. It has met with general approval and forms the subject of a recent paper by Mr. J. Cooper,§ who discussed the lamp mainly in its application to rescue operations. For such a purpose the head-lamp has the outstanding advantage over the electric hand lamp that it leaves both hands free. In operations such as that shown by Fig. 15: in travelling or carrying a stretcher in a low place; in applying artificial respiration underground; in handling a water hose or using a portable telephone, to have two hands available and yet to get a good light thrown upon the point at which the eyes are directed is of incontestable value.

W. WALKER.
J. S. HALDANE
H. BRIGGS

†MS. information from Mr. J. T. Ryan.
‡ J. B. Snelton, Trans. I. Min. Engs. LVII, p. 142.
Fig. 14.—Briggs Equalizing Arrangement and Air Tube.
FiG. 15.—Electric Head Lamp in Use.
FIG. 16.—Briggs Compressed Oxygen Rescue Apparatus.
APPENDIX I.

THE BRIGGS COMPRESSED OXYGEN MINE RESCUE APPARATUS.

(a) General Arrangement.—In designing this apparatus it has been the aim to produce an appliance capable of satisfying the needs of the wearer while he is undertaking the hardest work, and one with which the least possible part of the man’s attention is directed to the apparatus, so that he may be free, with both brain and hands, to carry out the duties he has to perform.

Fig. 16 shows the apparatus being worn, and Fig. 17 (not to scale) is its flow-diagram, the arrows indicating the direction of the air-stream.

The oxygen delivery, like that of several other apparatus, is set at the uniform rate of 2 litres per minute, and is augmented, when occasion arises, by means of a by-pass. Early in the research, attention was directed to the self-regulating oxygen-feed devices first introduced by Garforth, and developed more recently in America by Gibbs and Paul. It was recognised that a maximum economy

![Briggs Rescue Apparatus, flow diagram.](image-url)
in oxygen may be realised with such devices, and, therefore, that if a party trapped by a fall of roof on their line of retreat, the apparatus would ensure the men (sitting still) for a long time. The self-regulating feed, however, was adopted for the new apparatus because it is believed that, no matter how mechanically that kind of feed may be, its drawbacks outweigh its advantages. In most of the work to be done by rescue apparatus 2 litres of oxygen per minute are more than sufficient; the excess, which blows off, serves the useful end of clearing away nitrogen from the circuit. In this country we have had in certain areas still have, the trouble of impure oxygen. Impure oxygen is especially dangerous in apparatus with automatically-controlled valves, particularly in an accumulation of nitrogen within prevents deflation and thus prevents the automatic feed functioning. Accidental inward leakage, as at the mouthpiece, is insufficient to give rise to distress from CO (if present), may add sensibly to the residue of nitrogen. To obviate the effects of nitrogen-accumulation in such apparatus, it is either necessary to by-pass systematically or to arrange for a continuous slow discharge to waste from some point of the apparatus not under positive pressure; the former method deflects too much of the attention of the wearer to his apparatus, and the second involves an additional complication while both methods seriously detract from that economy in oxygen consumption which is the main advantage of the automatic control. Further, the automatic feeds so far designed are mechanically more complex than the constant dead-man valve, and correspondingly more apt to be thrown out of adjustment.

Similar reasons dictated against the adoption of the variable oxygen feed, adjusted by the wearer; the nitrogen evil is almost equally pronounced; the failure through underfeeding is much enhanced; proficiency is more difficult to acquire and maintain, and far too much of the man's attention is engrossed by apparatus.

In the present apparatus, the possibility of a team being trapped and having to eke out its oxygen as long as possible has not been overlooked, and is referred to below.

The apparatus is altogether carried on the back (in this respect resembling the Weg, Tissot, and Gibbs), thus giving freedom for the arms.

The body belt is the three-inch, webbing, infantry belt which proved its admirably serviceable during the war.* The slings, which are padded at the shoulders, are of narrower webbing of the same quality; their lengths are adjusted by aid of a simple device. The slings are connected to the frame by means of spring hooks.

The parts of the apparatus are supported on the back by the frame F (Fig. 16 and 17), which is of steel aeroplane tubing, 1 in. in diameter, weighing ½ lb. per foot, and made by the Chesterfield Tube Co., Ltd. The frame also constitutes the greater part of the breathing circuit.

The mouthpiece, flexible tubes, T, and purifier, P, make up the remainder of that circuit.

The flexible tubes, T, which pass over the shoulders, are those which were provided with the first pattern of Army box respirators. They are highly flexible and do not have any wire rings.

As Fig. 17 indicates, the air leaving the mouth passes through the valve and having circulated through the purifier, flows along the part of the marked "cooling tube" and enters the bag at A. On inspiration, the air is led from the bag through the valve V₂ and into the lungs. The oxygen stream then leaves the circuit at D.

(b) Oxygen Cylinder.—The oxygen cylinder, C, is 13 inches long and 4½ inches in diameter. It holds 290 litres of oxygen at 120 atmospheres, and about 330 litres at 150 atmospheres pressure. For practice purposes the former pressure will give an ample supply for two hours, while under emergency conditions, by raising the pressure to the latter figure, the supply may be made sufficient for at least 4 hours. The weight of the cylinder, without valve, is 7 lbs. The test-pressure is 25 atmospheres, at which pressure there must be no permanent set. The cylinder is supplied by the Mills Equipment Co., 56, Victoria Street, London, E.C.
by the Chesterfield Tube Co., Ltd., and the Research Committee is considerably indebted to Mr. H. Trevorrow, of that Company, for his interest and energy in producing this article to Dr. Briggs' specification. The Committee is also under obligation to the officers of the Technical Department of the Air Ministry, whose pioneer work on light cylinders during the war has been of much value. The metal used is a high grade carbon steel, having an ultimate tensile strength of 40 to 50 tons and a yield point of about 23 tons per sq. inch. The extremely light Air Ministry cylinders designed for aeroplanes were made of the same material, but as the metal remained under strain after manufacture, they could not be regarded as safe to use for any considerable time. The present cylinder, though heavier than the Air Board pattern, does not raise the same doubt as to persistence of strength; it is annealed at the works at 700° C. and the metal normalised—i.e., relieved of strain.

Instead of being rigidly attached to the rest of the apparatus, the cylinder is secured to the lower horizontal member of the frame by two stout leather straps. Metal loops prevent it shifting laterally.

(c) Cylinder Valve. The sunk-spindle valve of the Titan type, shown in Fig. 18, was designed with the object of getting a valve of the least weight and greatest compactness compatible with strength. After opening a valve with the key (Fig. 19),

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**Fig. 18.—Sunk Spindle Cylinder Valve, Briggs Apparatus.**

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**Fig. 19.—Key for Sunk-spindle Valve**
the leader of a team screws on the cap covering the sunk spindle, tightening it by means of the spanner-end of the key. In this way he guards against loss of clip along the valve spindle and makes doubly certain that there can be no tampering with the valve while the apparatus is in use. Such a valve precludes all possibility of it being accidentally closed, and offers little or nothing to catch against projection in travelling in a narrow road.

(d) Oxygen Feed Valve Gear.—Fig. 20 is a copy on a reduced scale of working drawings of this important part, which lies against the left-hand side of the body at the level of the waist. The gear comprises the reducing valve, by-pass pressure-gauge and flow-meter; it is connected by a stout union, C, to the cylinder. The high-pressure part of the gear is of gun-metal; the rest is of aluminium. Thoroughly tinning the gun-metal centre with "kalyon," an aluminium self-flux solder, it has been found practicable to cast the aluminium direct upon that core and to ensure a mechanically strong and gas-tight junction of the two metals.

The reducing valve, R, is of the single-lever variety, the lever being pressed against one side of its box by a spring, S, which makes sure that the valve has no transverse movement on its seat. No rubber enters into the construction of the reducing valve; the diaphragm, A, is a 2-inch German silver and diamond made by Messrs. Short & Mason, London. The metal diaphragm is of a delicate regulation, and is very susceptible to pressure changes; it has obvious advantages over rubber that it does not "perish," that it is stronger, and that its flexibility does not depend on temperature.

From the reducing valve box the oxygen flows through the resistance, r (see below), into the by-pass box, and thence through a 4 in. piece of stout rubber pressure tubing into the breathing circuit of the apparatus.

The by-pass, B, is worked by the pressure of the wearer's thumb, and under the action of a strong spring immediately the thumb is removed, the advantage of having a by-pass which can be operated instantly and which is self-closing, will be evident to all who have used rescue apparatus. The open at B is covered by a disc of strong leather or balloon fabric. The lever is permitted to have a very small movement, to prevent the valve suffering under too hard a blow when the thumb is suddenly taken away. The guard above B has been added at Mr. Walker's suggestion to reduce to negligible proportions the risk of the push-button being accidentally held down by contact, e.g., with the corner of rock.

The gauge, G, has two reading points and a double scale. The front registers the cylinder pressure, and the back one the rate of flow of oxygen litres per minute. The wearer can thus see at a single glance the extent of the oxygen reserve, and whether the proper discharge is being maintained. The reading window is arranged around the edge of the gauge cover, and, as gas is out of place in a rescue apparatus, it is made of non-inflammable celluloid. Applying a suggestion of Mr. W. Harris, of Ilanharran, the so-called "radium composition has been used to enable rough readings to be taken without having to shine a light on the gauge. Luminous spots are placed on the ends of the pointer, and the zero and 120-atmos. divisions of the pressure gauge and of the 2-litre division of the flow-meter are similarly marked by luminous spots of distinctive shape. Both gauges are of the Bourdon type and of ordinal commercial construction. They are arranged back-to-back in the same case. No iron or steel is used for pointers or for any other part, so that the gauge, along with the rest of the apparatus, can be tested for leakage under water without fear of rusting.

As with the Wag and Tissot apparatus, the gauge, while being rigidly strongly connected to the cylinder, is within view of the wearer. It does, however, project far enough to the front to be in the way when crawling; in the manner of suspending the cylinder ensures that, while on all-four, the oxygen feed gear and gauge automatically swing up and so give freedom for arms. This mode of attaching the gauge removes the necessity of a fixed connection between it and the cylinder. A high-pressure, flexible connecting tube has three objections; first, it is vulnerable and mechanically a weak point.
BRIGGS RESCUE APPARATUS
OXYGEN FEED GEAR AND GAUGES

SECTION ON XX

PART SECTION ON YY

SECTION ON ZZ

PLAN OF LEVER L_4

FIG. 20.
secondly, it is apt to get in the wearer’s way; and thirdly, it entails the gauge being placed in a pocket, making it necessary to free one hand to extract the gauge to read it.

From the manner of connection (Fig. 20), it will be seen that the flow-meter is merely a gauge registering the pressure in the reducing valve box, \( E \). As has already stated, the oxygen has to pass the resistance, \( r \), in order to escape from the reducing valve box. This resistance takes the place of the fine orifice placed on the out-flow side of other reducing valves; it consists of a packing of cotton-wool. The tightness of packing can be adjusted by a screw, \( E \). In practice it will be found that, once set, the need for readjustment of the resistance occurs very infrequently. In setting the resistance, the regulating screw of the reducing valve is given a mid-position; the oxygen discharge nozzle is connected to a reliable litre-meter (First Report, pp. 31, 32, 33); the oxygen is turned on, and the screw, \( E \), adjusted until the flow-gauge of the apparatus reads the same as the litre-meter. A discharge of about 2 litres per minute should preferably be selected for the purpose of this adjustment. The reason for adopting a resistance of the type described instead of the small orifice is two-fold; in the first place, as the number of paths of flow for the oxygen through the wool is extremely large, the chance of the channel being blocked by rust particles which have managed to evade the filter is almost infinitesimal; and, in the second place, with a resistance of this type, the rate of flow is almost directly as the pressure causing it, instead of being proportional to the root of the pressure as it is in the case of an orifice. In other words, we nearly attain, by these means, to a parallel of Ohm’s law, and in so doing, the flow-gauge scale-divisions become almost of equal width in place of being awkwardly crowded together at one end of the scale and few and far between at the other.

(c) The Purifier.—The purifier, or regenerator, is of a form which lends itself to being re-filled at the rescue station. It consists of a strong, rectangular, tinned-metal case divided into two compartments by a horizontal partition. The canister is so made that its strength and security depend as little as possible on solder, since plain soldered joints continually in contact with caustic soda soon deteriorate. In Fig. 17 the left-hand end of the can forms the lid. The lid has a flange, 1 in. deep, which fits over the body of the can. Many methods were tried of attaching the lid to the body, and were discarded, one after another, because of their complexity or because they gave insufficient security against leakage. That finally adopted was to run a thin strip of tin round the joint and solder it to both lid and body. So sealed, the canister can be quickly opened, as a bully-beef tin is opened, by tearing off the strip, and neither lid nor case is damaged by the operation. One quickly becomes expert in making such a seal with the soldering iron, and the small additional trouble involved is repaid by the safety and strength of the joint. The solder, being external, is not in contact with the alkali.

Into each compartment of the canister there slides a carrier consisting of a rough-shaped piece of thin tin having upright ends of stout gauze. The top of the carrier is open. After the two carriers have been filled in the manner described below they are pushed into place, the lid is sealed on, and the cartridge is ready for use.

The caustic soda absorbent is supported in each carrier upon twelve light trays of stamped or crimped gauze, each tray being 7½ ins. by 4½ ins. The weight of metal in the purifier, including the carriers and gauzes, is 4½ lbs.

Three essential conditions have to be fulfilled in regard to the support of the absorbent in the cartridge. These conditions are: (a) the alkali must be uniformly distributed between the trays and over each part of a tray; (b) each individual granule or stick must have plenty of room in which to expand, and (c) the granules or sticks must be so caged that when the cartridge is jolted, they are prevented from moving out of place and accumulating at one side or at one end of the box. In the course of a long series of experiments, three methods of crimping or moulding the gauze trays (together with the necessary dies and other devices to perform the crimping) have evolved which may claim to satisfy these conditions:

(1) The first method (first tried in 1917) is only suitable for caustic sticks; granules tend to shift if the cartridge is jolted while standing on its end. The
ordinary caustic soda stick having proved unsatisfactory for the purpose, Mr. Crosfield, Ltd., of Warrington, kindly made up a quantity of sticks ½ in. in diameter which gave excellent results in the fluted gauzes of Fig. 21. In arrangement the gauze in each compartment of the purifier is in a single layer, it being crimped in a special machine to form—as the figure shows—a number of straight channels, constituting a set of air passages "in parallel." The diameter of each tubular channel is ½ in. The crimp being placed on end, the sticks are dropped into the channels. The only objection to the method is the expense of the thin caustic sticks, whose cost will probably always lead to the second or third method being used in practice.

(2) In the second manner of crimping, dating from 1918, the gauze trays are preferably made separate instead of being connected together in one piece. Otherwise, when the trays are in position, their cross-section is similar to Fig. 21. If a channel be followed down, it will be found to be obstructed at three or four points along its length, either by cross-rolls in the gauze, or by the crimp suddenly stepping half its diameter to one side or the other, or by aid of an equivalent expedient. In this form, the trays (which are loaded from above) are suitable for receiving granules, since the obstructions prevent the granules from being shaken to one end of the box, and thus prevent the cartridge choking if it is put into use. Cartridges filled in this manner have given excellent results.

(3) A useful variant on the latter arrangement was suggested by Lionel Rosling in 1919. The gauze trays are made to receive hexagonal-depression, the character indicated by Fig. 22, which is a photograph of one half of the die used in pressing the trays. The caustic granules are scattered evenly in the depression. By turning the trays alternately end-for-end when putting them in the carrier, the ridges are "staggered," i.e., a ridge is made to lie in a depression of the tray above, and vice versa. The arrangement has proved successful; it ensures that the granules staying in their proper places no matted the cartridge may be shaken after filling.

In each of the methods described, it is found advisable to insert three or four layers of blotting paper in each compartment. One strip lies at the top, where it is up against the roof of the compartment and makes a sufficiently tight seal at that place; the others are respectively placed between trays at one-third, two-thirds of the depth of the compartment. The latter strips catch and guard any drops of caustic solution falling on them.*

* By the use of the forms of cartridge described above, it has been possible to get highly efficient absorption of CO₂ and very low resistance. The latter has been secured by splitting the air, so that it traverses a compartment by a considerable number of parallel paths.

The purifier is attached to the frame by two stout brass unions, which are provided, in place of the milled nuts commonly used for rescue apparatus.

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* Attempts were made in 1917 to place the granules in crimped blotting paper in place of the gauze, but the idea was speedily abandoned as the crumps almost invariably caught fire spontaneously in the cartridge.
Fig. 22.—Die for stamping Gauze Trays, Briggs Apparatus.
hexagonal nuts to enable them to be securely tightened by a key. At the middle of the opposite end of the can there projects a short brass knob, which engages with a strong and simple catch and forms a third point of support for the cartridge.

As the results reveal (p. 52), a charge of 2 lbs. of caustic granules is adequate to outlast the oxygen supply during the walking test outlined on p. 22. In an actual emergency, however, and especially if the apparatus has to be used in a hot place, it is preferable to employ 4 lbs. of granules: not on account of carbon dioxide, but because the heavier charge gives cooler air. So far as carbon dioxide is concerned, it is found that a 4 lbs. charge is capable of abstracting the CO₂ discharged by a man walking at 4 miles per hour for 3½ hours, at the end of which period the CO₂ in the inspired air rises above 2 per cent. (see p. 53).

(f) Insulation of Purifier.—The purifier is heat-insulated, not only at the side nearest the wearer (where there is also an air-space between it and the man’s back), but on all six sides.*

The principal reason for enveloping the can as completely as possible with an insulating medium, is to prevent, or, at any rate, considerably to reduce, the dripping of the caustic inside. Dripping is due to the over-accumulation of moisture by particles of soda which, under the influence of increasing warmth, become more and more fluid and finally fall. In falling, a drip probably collides with another moist granule and induces that also to drop through the gauze. Sometimes a vertical channel, altogether clear of caustic and running the complete length of a compartment, has been observed to form in this manner. Such

![Fig. 23.—Method of Insulating Purifier: Briggs Apparatus](image)

a channel becomes an easy path for the air, which passes through without being properly scrubbed. Usually these channels lie against or near a cool metal surface, which has doubtless acted as a condenser of moisture during the early part of the “run”; and hence the need for covering such surfaces with a non-conductor. After trying several others, a, light and strong insulator was found in the material called *leatheroid*, supplied by Messrs. Millionite and Insulator Co., Ltd., Walthamstow, London, E. The mode of application is illustrated by Fig. 23 where a is part of a cartridge and b the leatheroid cover. The latter is formed of two sheets, one corrugated and the other plain, which are fastened together by small duralumin rivets. The corrugated side is placed in contact with the can. The envelope is in one piece.

(g) The Bag.—Like those of the Douglas respiration apparatus and the Gibbs rescue apparatus, the bag is wedge-shaped. It lies on the shoulders and has a capacity of about six litres. The bottom, the two V-shaped sides and the part which lies against the wearer’s back are made of stout balloon fabric supplied by the North British Rubber Co., Ltd., Edinburgh. The remaining side, f, Fig. 16, is a sheet of duralumin or brass which has been blackened by chemical

* The only other breathing apparatus with a completely enclosed cartridge is the Weg, where the cartridge is carried in a leather case.

Duralumin.—This valuable alloy—frequently mentioned in the course of this description—is made by Messrs. Vickers & Sons. Its specific gravity is approximately that of aluminium, and its strength (after proper heat treatment) nearly that of mild steel. It is tougher and springier than aluminium and forms excellent screw threads.
means (not by paint or lacquer) to obtain a good radiating surface. The sheet is hung from a horizontal member of the frame by strong hinges. Three advantages proceed from having this outer side of the bag of metal: (1) An additional radiating surface is obtained to assist in cooling the regenerated air; (2) The sheet affords mechanical protection and considerably reduces the chance of the bag being damaged by a sharp projection; and (3) Excepting when there is a large leak in the breathing circuit, the weight of the sheet maintains positive pressure within the circuit. In the case of a large leakage the bag flattens and cannot be kept distended.

The coupling to the bag is such as to prevent the metal side suddenly distending the pipe leading from the bag when the latter is sucked almost empty.

By carrying the uprights of the frame outside in the manner shown by Fig. 23, one guards against the bag being suddenly pressed flat.

It is only when there is a serious leakage that the bag is drawn empty towards the middle of a breath. In normal use, when the bag is becoming deflated there is some consumption of oxygen being in excess of the feed, the metal flap is first allowed to touch down at the end of an inspiration; the by-pass is then pressed and the bag re-inflated during the next expiration.

(h) The Inspiratory and Expiratory Valves.—For reasons which follow from the results of the tests on rescue apparatus valves described on p. 32, the brass valves adopted are of the Rosling pattern and of a size specially made for present apparatus by Messrs. The Isleworth Rubber Co., Ltd. The valve boxes are attached to the tubular frame at its topmost points. By making the boxes also serve as unions connecting the frame and the flexible tubes, two joints are eliminated. The boxes, which are shown in section by Figs. 24 and 25, are of duralumin. The screws have strong, coarse threads, the unions being meant to
tightened hard by a key instead of screwed up by hand. The rubber valve is carried by a hollow thimble, \( t_1 \), \( t_2 \), which is of identical pattern in each case. Matters have been so arranged that if either valve be put into its box the wrong way up, the union is prevented from engaging its screw; also that if a valve be omitted, it is impossible to tighten the joint, owing to the female screw of the union being cut away at \( a_1 \), \( a_2 \). Again, it is made impossible for the half-joint belonging to the flexible inhalation tube to be coupled in mistake to the exhalation side, or vice versa. In other words, there is only one way of connecting up these joints, and that is the correct way.

(j) The Relief Valve.—The valve is placed at \( R \), Fig. 17, where it discharges condensed moisture as well as excess air. It functions automatically (being set to blow off at about 4 ins. water column), and it can also be worked by hand if desired. Fig. 26 is a section of the valve showing how it is fitted in the brass angle-piece. Because of its proximity to the purifier, the moisture draining into it is often alkaline, and thus neither aluminium nor aluminium alloy may be used in its construction.

(k) The Frame.—The steel tubular frame is silver-plated. As it is advisable to conserve the heat as much as possible in the expired air flowing towards the purifier, the portion of the frame between the expiration valve and the cartridge is left bright, so that its heat-emissivity may be a minimum. The remainder of the frame serves as a cooling tube; the silver plating of that part is therefore sulphided to obtain a dull black surface of high emissivity.

(l) The Saliva-trap and Mouthpiece.—(1) The metal portion of the mouthpiece is of the Tissot pattern, and is shown in Fig. 27. It being preferable to catch the saliva as near the mouth as possible, the saliva-trap and metal mouth-fitting are made in one piece. A simple conical valve, controlled by a spring, enables the trap to be emptied. To clear the saliva trap, the valve is drawn down and a sudden puff of air is ejected from the lungs, when the saliva is thrown out in

![Fig. 26.—Relief Valve, Briggs Apparatus.](image-url)
a forward direction. The valve stalk is then released. When the valve is shut, the saliva accumulating above it makes a most effectual seal. Devices were considered having the object of automatically closing the connection between

![Diagram](image)

and the mouth when the discharge valve was opened. Such a precaution is deemed unnecessary. The natural thing to do in spitting is to blow out; not draw in.

Tissot’s saliva-trap has been improved by adding the inclined strip, a, (Fig. 27), which makes it impossible for the saliva to run back into the mouth, no matter how the head may be held.

(2) The rubber part of the mouthpiece has been designed for attachment to a head-dress described below. It can be obtained from Messrs. J. E. Baxter & Co., Leyland, Preston. For the sake of safety, the flange has been made as large as practicable. The lugs gripped by the teeth are in all dimensions larger than usual. With other mouthpieces the lugs are so thin that the teeth have to be closed to get a firm hold. The resistance to heavy breathing through clenched teeth is very considerable, and when doing hard work while using a mouthpiece of an old design, anyone with a complete set of teeth is compelled to release the lugs and to open the jaws. To enable the grip to be maintained during heavy exertion, the lugs of the present mouthpiece are thickened. In Fig. 28 the man is wearing an ordinary mouthpiece, which was cut level with the flange to make the teeth more visible, and in Fig. 29 he is using one of the new pattern. In the first photograph the teeth are closed; in the second they are open.
Fig. 28.—Position of Teeth when using ordinary mouthpiece.

Fig. 29.—Position of Teeth when using mouthpiece of Briggs Apparatus.
To assist in making the hold on the lugs more secure they are, like the stem of a tobacco pipe, moulded with swellings at their extremities. Mr. Winborn called attention in 1918 to the desirability of such swellings; a recent Weg mouthpiece and one variety of the army mouthpiece also have lugs with thickened ends.

There are no tapes fastened to the mouthpiece; their absence facilitates disinfecting.

(\(m\)) Headdress and Noseclip.—The cap is of skeleton pattern, wide holes being left to allow of ventilation when working in a hot place. The circumstances of any case will decide as to the advisability of using a further head covering in addition to the skeleton cap.* The cap is made of sail cloth, strongly bound at its edges with wide bootmaker's braid, and at the front elastic bands are provided to enable the cap to adjust itself to the wearer's head. These bands are similar to those used by the Germans for their gas helmets during the war, each consisting of two steel springs enclosed in cotton fabric. The springs are silver plated so as to be unaffected by moisture. Unlike rubber elastic, this variety does not lose its "nature" in course of time. The cap serves to support two cheek plates (due to Lient. Rosling) to which the nose clip and rubber mouthpiece are hooked. A cheek plate is of duralumin with a layer of felt riveted to the side which lies against the face. The bands supporting the cheek plates are specially made of non-fraying webbing by Messrs. Rawle, Jermy Street, London, S.W., and each can be adjusted in length by a simple wedge device.

The nose clip is of the screw pattern, and was developed from a clip that has been in use at Wath Rescue Station for some years. Being secured to the cheek plates in the manner shown by Fig. 16, the clip is difficult to displace, and its security is increased by the metal bridge of the clip passing under, instead of over, the nose; there is thus nothing projecting in front of the nose to be caught or to be struck by a chance blow. In addition to its security, this clip proves most comfortable to wear, since the degree of pressure upon the nostrils can be regulated so as to be sufficient to close them without being excessive.†

(n) Emergency Oxygen Feed.—As has been stated, the captain of a team carries the key (Fig. 19) with which the oxygen cocks are turned on. In the case of a team being trapped and unable to return to its base, it is intended that the captain should, by means of the spanner end of the key, remove from the reducing valve of each apparatus the adjusting screw and spring controlling the pressure on the diaphragm. It will then be found that the valve gives an oxygen flow of about 0·4 litre per minute, which is sufficient to sustain a person sitting or lying still, especially as the by-pass is always available in case the supply needs to be supplemented. In the rare, but nevertheless possible, contingency under consideration, a team would in this way be enabled to eke out its oxygen for many hours.

(o) Weight.—The complete apparatus, charged with 3 lbs. of caustic soda granules, weighs 29 lbs.

Records of Tests with the Briggs Apparatus.—The apparatus has been subjected to a number of tests carried out by various persons. These tests uniformly involved greater respiratory exertion than is likely to be needed, in the same length of time, during actual service in the mine.

In all cases the reducing valve was set, at the beginning of a "run," to give 2 litres of oxygen per minute. The purifier was charged with granulated caustic soda of the weight stated in each instance. The temperature rise is the difference

* It is of interest to state that as early as 1906, an openwork cap was used with the Weg apparatus. In that instance, the crown of the cap was of string net. The object, as in the present instance, was to provide copious ventilation for the head.
† Early in 1919, the Department of Scientific and Industrial Research, at the desire of the Mine Rescue Apparatus Research Committee, issued a pamphlet on nose clips. The pamphlet illustrated a clip resembling that described above and a modified Proto skull cap to which the clip was attached. The present headdress is an advance on that of the pamphlet. About 20 of the combined headdress noseclip and mouthpiece of Fig. 16 were distributed to rescue station instructors and others towards the middle of 1919.
between the temperature of the inspired air and that of the outside atmosphere. Carbon dioxide determinations were made with the Haldane gas-analysis apparatus.

Endurance Tests.—In these the subject walked for two hours, or for the time specified, at 4 m.p.h. round a level court. The routine set forth on p. 22 was exactly followed.

(1) Subject H.B.—Four lbs. caustic soda.

After walking ½ hour: CO₂ nil; temperature rise, 9°F.
  1 hour: CO₂ nil;    11°F.
  1½ hours; CO₂ nil;  23°F.
  2 hours; CO₂ nil;    25°F.

The subject then ran 400 yards at about 5½ m.p.h., after which the CO₂ percentage was again found to be nil. The temperature rise was 35°F. Resistance of the whole circuit (mouthpiece to mouthpiece) to a flow of 85 litres per min. measured after the run, 1-3 ins. w.g.

(2) Subject D.D.—An exact repeat of (1).

After walking ½ hour: CO₂ nil; temperature rise, 4°F.
  1 hour: CO₂ nil;    10°F.
  1½ hours; CO₂ nil;  14°F.
  2 hours; CO₂ nil;    17°F.

After running an additional 400 yards, CO₂ 0·21 per cent.; temp. rise, 24°F.

(3) Subject C.R.—An exact repeat of (1), except that the running at the nil was omitted.

After walking ½ hour: CO₂ nil; temperature rise, 12°F.
  1 hour; CO₂ nil;    13°F.
  1½ hours; CO₂ nil;  21°F.
  2 hours; CO₂ nil;    28°F.

(4) Subject D.D.—The same test repeated, but with a charge of 3 lbs. grained caustic soda in the purifier.

After walking ½ hour: CO₂ nil; temperature rise, 9°F.
  1 hour; CO₂ nil;    19°F.
  1½ hours; CO₂ 0·35%;  23°F.
  2 hours; CO₂ 0·78%;    33°F.

After running an additional 400 yards, at about 6½ m.p.h., CO₂ 0·78 per cent. temp. rise, 39°F. Subject preferred the heavier charge of caustic, because the air was then cooler. Resistance of the whole circuit to a flow of 85 litres per min. measured after the run, 1·4 ins. w.g.

(5) Subject R.M.C.—The same test repeated; 3 lbs. caustic soda.

After walking ½ hour: CO₂ nil; temperature rise, 5°F.
  1 hour; CO₂ nil;    28°F.
  1½ hours; CO₂ 0·24%;  36°F.
  2 hours; CO₂ 0·19%;    29°F.

(6) Subject J.C.—The same test repeated, but with only the upper compartment of the purifier charged with 2 lbs. caustic granules.

After walking ½ hour: CO₂ nil; temperature rise, 6°F.
  1 hour; CO₂ 0·18%;    18°F.
  1½ hours; CO₂ 0·41%;  23°F.
  2 hours; CO₂ 0·17%;    25°F.
  2¼ hours; CO₂ 1·57%;    24°F.

(7) Subject R.M.C.—Repeat of (6); 2 lbs. caustic soda.

After walking ½ hour: CO₂ nil; temperature rise, 13°F.
  1 hour; CO₂ 0·18%;    31°F.
  1½ hours; CO₂ 0·82%;  34°F.
  2 hours; CO₂ 1·32%;    32°F.
Climbing Test. Subject H.B.—The test consisted in climbing Arthur's Seat, Edinburgh, and was to ascertain the behaviour of the apparatus under sustained heavy exertion. The climb (involving a vertical rise of 640 feet) was performed without difficulty or incident in 21 minutes, and the descent to the starting point in 9 minutes. In ascending, the subject did over 100,000 ft. lbs. of external work; his oxygen consumption on the upward journey averaged about 2·8 litres per minute. A full charge (4 lbs.) of caustic soda was used. Samples of air for analysis were withdrawn from the inspiration tube at the summit and after descent. Owing to the breeze the cooling of the air was highly efficient.

On reaching summit; CO₂, 0·43%; temperature rise, 4° F.
bottom; CO₂, 0·12%; " 4° F.

Exhaustion Tests on Purifier.—To ascertain the full capability of a purifier charged with 4 lbs. caustic granules, and to what extent it outlasts the oxygen supply, the wearer walked on the level at 4 m.p.h., the temperature readings and air samples being taken in the manner stipulated on p. 22. The oxygen cylinder was recharged when exhausted and the test continued. The times stated below do not include those occupied in recharging the cylinder. The subjects worked in shifts of 1¼ hours, the apparatus being handed over to another man after such a shift.

Subjects D.P. and C.R.

After walking 4 hours; CO₂, nil; temperature rise, 4° F.
1 hour; CO₂, nil; " 14° F.
1½ hours; CO₂, nil; " 26° F.
2 hours; CO₂, 0·12%; " 14° F.
2½ hours; CO₂, 0·24%; " 26° F.
3 hours; CO₂, 1·60%; " 32° F.

After walking 3 hours 6 mins. and then running at 8 m.p.h. for 2 mins.

Subjects H.B., D.P. and D.D.

After walking 4 hours; CO₂, nil; temperature rise, 3° F.
1 hour; CO₂, nil; " 9° F.
1½ hours; CO₂, 0·12%; " 15° F.
2 hours; CO₂, 0·25%; " 15° F.
2½ hours; CO₂, 0·30%; " 25° F.
3 hours; CO₂, 1·32%; " 25° F.
3 hrs. 21 mins.; CO₂, 2·47%; " 17° F.

Sudden Exertion Tests.—In these tests the wearer of the apparatus walked for 26 minutes at the rate of 3 m.p.h.; he then ran 300 yards at 6·7 m.p.h., after which he walked for 2 minutes at 3 m.p.h., when the samples and readings were taken. This routine was repeated four times, occupying two hours in all.

Subject B.B.—Four lbs. caustic soda.

Walking 26 mins.; running 300 yds.; walking 2 mins.; CO₂, nil; temperature rise, 9° F.
second spell; CO₂, nil; " 19° F.
third spell; CO₂, 0·12%; " 27° F.
fourth spell; CO₂, 0·25%; " 33° F.

Resistance of whole circuit to flow of 85 litres per minute, measured after the test, 1·7 ins. w.g.

Subject J.C.—Four lbs. caustic soda.

Walking 26 mins.; running 300 yds.; walking 2 mins.; CO₂, nil; temperature rise 6° F.
second spell; CO₂, nil; " 10° F.
third spell; CO₂, nil; " 18° F.
fourth spell; CO₂, nil; " 22° F.

Resistance of whole circuit to flow of 85 litres per minute, measured after the test, 1·6 ins. w.g.
APPENDIX II.

FITNESS TESTING WITH THE ERGOMETER.

The apparatus named is the bare minimum needed, and the description given is of the method reduced to its simplest form.

Apparatus: (1) Martin’s Ergometer.—The machine is to be seen in Fig. 4, which shows the arrangements at the Physical Test Station. It consists of a bicycle frame and seat, a heavy fly-wheel having been substituted for the back wheel of the bicycle. Round the fly-wheel passes a belt, the ends of which are connected by adjustable cords to spring balances. The belt is of linen or cloth, wires being run through the hems at each side of the strip of cloth, to prevent the belt slipping off the wheel. Care should be taken to dry the cord thoroughly before using, or the balance readings will be found to fluctuate. The pendulum, hung to be constantly in view of the subject, gives the rate of speed pedalling. With the size of fly-wheel and gear-ratio of the cycle usually supplied for the ergometer, the pendulum can conveniently be adjusted to make 50 swings a minute, since at that rate of pedalling the work done in foot-pounds per minute is obtained by multiplying the difference of the balance readings (in pounds) by 1,000. Whatever may be the rate of pedalling selected, the product of the difference of the balance readings and the distance (in feet) moved per minute at a point on the circumference of the fly-wheel measures the work done in foot-pounds per minute. Various rates of work can be set by tightening or slackening the cords attached to the belt.

(2) Gas-analysis Apparatus.—Carbon dioxide analysis being all that is required in the simplified method, a Briggs apparatus (p. 51, First Report) proves serviceable and speedy, a burette graduated along its entire length being used, a caustic potash solution, instead of alkaline pyrogallol, being placed in the absorption pipette. One of the assistants is seen using this apparatus at B, Fig. 16.

(3) Douglas Bag.—The 60-litre size, fitted with a three-way aluminium stopcock is required. It is a bellows shaped bag of convenient form to collect expired air. In Fig. 30 it is on the table, and a sample from it is being forced by pressure on the gas-analysis apparatus. When that operation is over, the bag, square empty, is connected to the rubber tube, A, through which the subject exhales. More usually it lies on the table at the side of the ergometer, thus keeping the connecting tubing short in length.

(4) Mouthpiece, Noseclip and Valves.—Any rescue apparatus mouthpiece and noseclip serves the purpose. The best valves are the Rosing type (see p. 31). They are obtainable from the Isleworth Rubber Co. The valve-boxes and Resi valves of the Briggs rescue apparatus (p. 48) will be found suitable.

(5) Connecting Tubing.—To avoid unnecessary resistance, the connections should be of one inch bore.

(6) Oxygen Supply Cylinders, Oxygen Collecting Bag and Bubbler.—The 100-ft. cylinders are the most serviceable. The cylinder in use is fitted with a reducing valve. From the reducing valve the oxygen is made to bubble through water and then to enter a distensible collecting bag. A cheap and useful form of bag is that used for holding coal gas on tradesmen’s small motor vans. The injection device described in the footnote, p. 12, may be placed immediately after the reducing valve to economise in oxygen. When the subject is breathing oxygen the reservoir bag should be kept about three-parts full. Over-distension of the bag may create sufficient pressure to force oxygen through both valves, and therefore, to be avoided. In Fig. 30 the reservoir bag is at C, under the table. The meter to be seen in that photograph enabled the volume breathed per minute to be recorded, and the movements of the pointer of the meter allowed the rate of breathing to be determined. For the sake of simplicity, however, the meter here omitted.

FIG. 30.—Testing with the Ergometer, Physical Test Station, Edinburgh.
Method of Conducting Experiments.—The subject, seated on the saddle, is fitted with the mouthpiece and noseclip. He breathes air from the room. While he is at rest the 3-way tap is turned, at the end of an expiration, to the “on” position, that is, so that the breath passes into the Douglas bag. It is kept in that position for a period of about two minutes, when the tap is turned off at the end of an expiration. The Douglas bag, now partially inflated, is put on the table; kneaded to mix its contents; connected to the supply tube of the Briggs analysis apparatus, and, with the tap in the “on” position, squeezed to force a few litres of the products of expiration through the burette. The sample so obtained in the burette is then analysed for CO₂. This procedure avoids the need for sample tubes or sample bottles.

The Douglas bag is then emptied by pressing it flat, and is again attached to the expiration tube connecting to the mouthpiece. The tap being in the “off” position, the subject is required to pedal (at the rate of the pendulum) at no load, i.e., with the belt off, for a timed period of 2 minutes. At the end of an expiration the tap is turned “on” and expired air allowed to accumulate in the Douglas bag for another 2 minutes of pedalling. The tap is again turned off after an expiration and the CO₂ percentage determined.

The belt is put in place; its cords are adjusted to give a difference of 3 lbs. between the balance readings, and the same sequence of operations is followed. Similar observations are made at balance-differences of 6, 9 and 12 lbs. Longer pauses should be allowed between the higher loads to allow the man to recover fairly completely from the effect of one spell of exercise before attempting another. Effort should be made in all cases to sustain the load for two timed minutes before allowing expired air to enter the Douglas bag. This preliminary interval has to be cut down on the highest loads (12 lbs. or 14 lbs.) as no one in our experience has been able to bear them two minutes or more; but in no case should the preliminary period be reduced below one minute. The interval spent in inflating the Douglas bag, however, can be safely reduced to 30 seconds or so when the work is severe, providing that the tap is opened and closed at the same phase of breathing—preferably at the end of expiration. A record wherein the correct rate of pedalling is not maintained must be discarded.

After this series of results has been obtained with the subject breathing air, an exactly similar series (excepting that the resting experiment may be omitted) is taken with the man breathing oxygen from the reservoir bag. Before the latter measurements are taken, however, it is advisable that he should breathe oxygen for about 10 minutes to swill out most of the nitrogen in solution in the blood and tissues.

Recording and Interpreting Results.—A test carried out in the above manner furnishes data such as those of Table I, p. 12.

The data are best set forth in the form of graphs in which the loads are plotted as abscissae and the CO₂ percentages as ordinates. Figs. 31 to 37 reproduce such graphs; the curves drawn in full lines show the relation between load and expired CO₂ percentage when breathing normal air; those in dotted lines that relation when breathing oxygen. The CO₂ proportion when the subject is resting and breathing air is in each case indicated by an arrow-head. Figs. 31 and 32 are constructed from the data of Table I.

It will be observed that the curves are in all instances dome-shaped; the CO₂ percentage rises from the resting value to a maximum and then falls again. The fall indicates oxygen-want. The immediate effect of the oxygen supply being less than the demand is to increase the lung ventilation. Enhanced breathing, which with the high loads becomes hard panting, dilutes, through sheer excess of air, the CO₂ discharged, and the CO₂ percentage accordingly drops. The load yielding the maximal CO₂ percentage (the “crest load”) may be taken as demarcating between normal load and overload. In other words, the man can sustain loads up to the crest value for some considerable time, as his oxygen input is adequate to deal with such rates of work; but he can only bear loads above the crest value for a brief period.
FIGS. 31-33.—Ergometer Testing; Graph records.
A useful measure of the stamina of a man (i.e., his power of supporting sustained physical effort) is furnished by the position of the crest load; the higher it is the better. The crest load, when breathing enriched air, of a strong man in the prime of life and inured to labour, is generally over 9,000 ft. lbs. per min. It is doubtful policy to keep in a rescue brigade (except, perhaps, as leader) anyone whose crest load on oxygen is 6,000 ft. lbs. or less.

The difference made in these records by condition or fitness becomes clear when the graphs of Fig. 31 are contrasted with those of Fig. 32. In the former case the subject is a relatively unfit, sedentary person, while in the latter he is an Army instructor in physical drill, who was selected for experiment by the Scottish Command as representing physically the best the Army can produce. The curves of Subject II diverge, while those of Subject VIII are practically coincident. A simple and useful method of expressing the fitness of a subject is to divide the crest-ordinate of the "air" curve by that of the "oxygen" curve, the level of
the arrow-head (CO₂ value, resting) being used as datum for each measurement. By that system the fitness of Subject II is 46 per cent., while that of Subject V is 100 per cent. The fitness of the healthy working miner usually exceeds 75 per cent.; evidently it is advisable that a permanent brigade member should also be at least as fit.

**Notes on the Subjects of the Accompanying Graphs.**

Subject II.—Sedentary person: weight, 136 lbs.; fitness, 46 per cent. Would much easier on oxygen than on air. The subject would probably respond favourably to physical drill, though his power of dealing with sustained exertion would never be large.

Subject VIII.—Regular soldier: weight, 168 lbs.; instructor in physical drill; athletic type; fitness 100 per cent. Judging by his general behaviour while doing work (quite apart from the results obtained), he is the fittest man we have tested. Breathing oxygen is not the least beneficial until the crest load is exceeded; then it gives a gradually increasing assistance.

Subject VII.—Manager of a mine working steep seams: trained rescue man; weight 189 lbs.; fitness 88 per cent. His daily work involves a lot of clambering in steep, low roads. Slow, deep breather. The high level of the CO₂ percentages and the corresponding small volumes taken into the lungs per minute are noteworthy features. Thoroughly suitable as member of rescue brigade.

Subject I.—Miner (repairer) working in steep seams: weight, 154 lbs; trained rescue man; fitness, 83 per cent.; high stamina; thoroughly suitable as member of rescue brigade.

Subject V.—Member of resident brigade for 2 years; previously a miner; weight, 142 lbs. This man was selected to see if the fitness of these brigade members deteriorates owing to their light duties, and the results, when compared with those of men constantly working underground, indicate a considerable falling off in both fitness and stamina. Fitness, 56 per cent.; unusually rapid breathing at the heavier loads. The fact that the subject breathed quicker on oxygen than on air for low loads may explain the crossing of the curves. The subject recently succumbed while wearing a defective rescue apparatus.

Subject P.T.S. 1/41.—Selected from the Physical Test Station records; infantryman of one of the older groups called up in 1918; age, 44; weight, 133 lbs; formerly a painter. *Introduced here to illustrate the deterioration that sets in with age. The report of the testing officer was:—"Stamina: Very poor. Condition: Poor. Observations: Not worth training; no use as infantryman. Recommendations: Suggest that he be set to his own trade."

Subject P.T.S. 1/24.—Selected from the Test Station records as a contrast to the last instance. Well-developed cadet of 19 years; weight, 175 lbs.; all-round athlete. The testing officer reported:—"Stamina: Excellent. Condition: Excellent. Observations: First-rate material; fit for anything. Probable increase of fitness from P.D., 10 per cent."
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Physical Exertion, Fitness and Breathing

Professor Henry Briggs, D.Sc.
PHYSICAL EXERTION, FITNESS AND BREATHING.

By HENRY BRIGGS, D.Sc., Professor of Mining, Heriot-Watt College, Edinburgh.

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PHYSICAL EXERTION, FITNESS AND BREATHING

By HENRY BRIGGS, D.Sc., Professor of Mining, Heriot-Watt College, Edinburgh.

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The experiments discussed in this paper were carried out during the research on mine rescue apparatus which was instituted in 1917 by the Scientific and Industrial Research Department. Their aim at first was limited to that of determining the oxygen consumption of persons engaging in different kinds of physical work, and with that object in view, a few tests were made by Dr J. S. Haldane and the writer on miners climbing inclines in the Newbattle and Lingerwood collieries, Midlothian; these were shortly afterwards supplemented by other tests on the same men in which weights were lifted and certain of the common tasks of the miner were performed. During the early trials the men breathed ordinary air; but as the wearer of a mine rescue apparatus has to breathe air highly enriched with oxygen it was judged necessary to study the influence of such air on a person's capacity for physical work. It had been a matter of experience to the members of the research committee that they could perform work with greater ease and comfort while wearing a rescue apparatus in good order, and thus obtaining air containing 70 or 80 per cent of oxygen, than under normal conditions. The writer, for example, can climb a mountain faster and with less fatigue when using an efficient mine rescue apparatus than without it, notwithstanding that the apparatus weighs, in its latest form, about 30 lb.

It was observed that an increased oxygen proportion in the air inhaled was uniformly helpful with persons of sedentary habits, but that working miners were tested little or no such benefit was derived; the

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1 The research committee consists of Mr William Walker, C.B.E., H.M. Chief Inspector of Mines (Chairman), Dr J. S. Haldane, F.R.S. and the writer. Summaries of these experiments have been published in the writer's paper on "Fitness and Breathing during Exertion," this Journal, 53, Proc Physiol. Soc. p. xxxviii, 1919, and in the Report of the Mine Rescue Apparatus Research Committee, 1920.
were in fact generally quite indifferent as to whether they breathed air or oxygen.

A long series of experiments was then commenced in which Martin's ergometer was principally used as the means of measuring the rate of exertion, and in which a quantitative and qualitative examination was made with subjects of various physique and training breathing air and oxygen. Thanks to the kindness of the Superintendents of Physical and Bayonet Training, Scottish Command and Aldershot, several soldiers specialising in different branches of athletics were included in the tests.

Subsequently, when it had become clear that the fitness of a subject could be measured by contrasting his respiratory performance when breathing normal air, and when breathing enriched air, the Army Council, acting upon the recommendation of Colonel Sir William Horrocks, K.C.B., and Lt.-Colonel E. P. Cathcart of the Army Medical Department, set up a Physical Test Station at which, up to the Armistice, the new method was applied for the examination of men sent in from units under the Scottish Command.

**Apparatus and Methods.**

The ergometer experiments were carried out in the Heriot-Watt College, Edinburgh, with Martin's ergometer\(^1\). During the experiments a pendulum, hanging in front of the subject as he sat in the saddle, provided the means of timing the rate of revolution of the pedals\(^1\). A rate of 56 revs. per min. was adopted throughout. At that speed, and with the gear-ratio of the particular cycle employed, the power expended, in foot-pounds per min., was ascertained by multiplying the difference of the balance-readings, in pounds, by one-thousand.

**Meters.** Two Milne dry meters were used. In each of them one revolution of the 8 ins. pointer indicated the passage of one cubic foot of gas. The dials were marked off in hundredths of a cubic foot. The meters were tested against displacement from time to time. The barometric pressure, temperature and hygrometric state of the gas being metered were kept under observation.

**Douglas bag and sampling apparatus.** A 60 litre wedge-shaped bag was used to collect expired air. The bag, which is part of the Douglas respiration apparatus\(^2\), is provided with a 3-way aluminium stop-cock which allows of the expired air being either discharged direct to the atmosphere ("off" position) or into the bag ("on" position). A small

\(^1\) For long-continued pedalling the pendulum is preferable to the metronome for this purpose; it is less trying to the nerves.
rubber tube connected to the bag enables samples of the contents to be drawn off for analysis. At first glass sampling tubes with taps at each end were used for this purpose, but they were soon abandoned in favour of small well-stoppered bottles, filled over a mercury trough. In the large numbers required the bottles were handier, simpler to use, less costly and much more easily replaced in case of breakage. A further simplification in taking samples for analysis was introduced at the Test Station.

_Oxygen cylinders and reservoir bag._ When the subject was breathing oxygen the gas was supplied from a 100 ft. cylinder fitted with a reducing valve. The oxygen discharged from the valve into a reservoir bag. At first the subjects complained of parching of the throat when breathing oxygen; the trouble was removed by causing the gas to bubble through water before entering the reservoir. The latter was kept about three parts distended during a “run.” Over-distension was carefully avoided, as with excess of pressure in the reservoir bag it became possible for the gas to push open both breathing valves and to discharge directly into the Douglas bag.

_Mouthpiece, valves and tubes._ The subject used a rescue-apparatus mouthpiece of rubber which fitted over one limb of a metal T-piece. The nose was closed by a clip. The air was directed to and from the mouthpiece by inspiratory and expiratory valves. Various valves were tried, the most successful being the Mueller water valve (Fig. 1) and the Rosling valve (Fig. 2). A Mueller valve of the dimensions indicated in Fig. 1 allows of the heavy breathing of severe exertion without introducing a degree of resistance appreciable to most persons.

The Rosling valve, adopted towards the end of the war for Army anti-gas purposes, is very free from resistance and low in slip. While Mueller’s is only serviceable for a stationary subject in the laboratory, Rosling’s is equally useful in the laboratory and in testing men marching or climbing in the open or in the mine. Unlike the mica disc valves frequently used in respiration experiments, it functions properly in any position. The valve is of rubber. A thin square of rubber, held by the corners, closes upon the flanged end of the tubular part of the valve (Fig. 2, left-hand view) and flexes away from it when allowing air to pass through (Fig. 2, right-hand view). The valve here illustrated was made for the writer by the Isleworth Rubber Company and adopted in the Briggs Mine Rescue Apparatus. Its resistance to a flow of 85 litres (3 c.f.t.) of air per minute is 0·35 in. of water column, and its slip is quite negligible. A not unimportant feature of the rubber valve is
noiselessness. When a valve makes a distinctive noise the subject's attention is apt to be directed to his own breathing, and the test may be vitiated thereby. The tubes leading to and from the mouthpiece were of one inch bore,—a size sufficient to reduce their resistance to negligible magnitude even with hard panting.

![Diagram of Mueller Water Valve](image1)

![Diagram of Rosling Valve](image2)

**Sampling tube for alveolar air.** A number of samples of alveolar air were taken while certain of the subjects were pedalling the ergometer. Essentially, the apparatus used for this purpose was that described by Haldane and Priestley(3); it consists of a long tube through which the subject can empty his lungs suddenly. To avoid the subject having to close the end of the tube with his tongue after such an expiration, as was done in Haldane's and Priestley's experiments, a wide-bore tap was fitted at that end; on this being closed the man could replace the rubber mouthpiece (which for the moment he had withdrawn) and continue working, leaving the experimenter to draw out from behind the tap a small sample of air for analysis. With the quickened breathing incident to physical work, it was not possible to get alveolar air samples after inspiration and after expiration as may be done under rest conditions. Most of the experiments were on men altogether strange to scientific methods; few were sufficiently trustworthy when it came to the difficult operation of providing a reliable alveolar sample while doing hard work.
Gas-analysis apparatus. In the main set of experiments, in which both oxygen and carbon dioxide were determined in each sample of expired air, the Haldane gas-analysis apparatus (4) was used. At the Test Station, where the routine was simplified and only CO₂ ascertained, the Briggs’ apparatus (5) was adopted.

Manner of conducting experiments. A number of preliminary trials were carried out in order to settle such matters as the rest period needed between spells of work on the ergometer, and the length of time work must continue before the breathing becomes sufficiently en rapport with the exertion to permit of reliable observations being made. After that, a regular routine, based on Douglas’ method, soon evolved, and the few changes subsequently made were merely to simplify the apparatus and connections and to improve the valves. This routine was as follows:

The subject, seated at rest on the saddle of the ergometer and fitted with the noseclip and mouthpiece attachment, inhaled air from the room, drawing it through one of the Milne meters. The Douglas bag (now empty) was connected to the exhalation tube with the 3-way cock in the “off” position to allow the products of respiration to escape into the room. When he had become accustomed to his position the cock was turned “on” at the end of an inspiration and the expired air began to enter the bag. A stop watch was started at the moment of turning the cock, and the number of inspirations was counted by watching the movement of the pointer of the meter. After about two minutes had elapsed, and again at the end of an inspiration, the tap was turned “off,” and the watch stopped. The bag was kneaded and one or more samples drawn from it. The volume in the bag was then measured by emptying the bag through the second meter. The necessary thermometer and hygrometer readings were taken. From these measurements and the time interval the volume exhaled per minute was calculated. The meter on the inspiration side enabled the quantity drawn into the lungs to be evaluated direct. Owing to the jerky action of the latter meter this determination did not reach the same degree of accuracy as that of the volume of exhaled air from the Douglas bag, but it was useful as a safeguard against gross error.

The second set of readings and samples were taken when the subject was pedalling with the belt off, i.e. when he was doing no external work. The same routine was followed, the man being required to pedal at the rate of 56 revs. per min. for at least two minutes before commencing to collect the expired air. After this, similar records were obtained with gradually increasing loads. Longer rest intervals were allowed between
the spells of work as the loads increased. The preliminary interval of two minutes' pedalling was strictly observed, except for the highest loads, such as 12,000 or 14,000 ft. lbs. per min., which are beyond the capacity of even the strongest men to sustain for long. With excessive loads the preliminary interval had perforce to be shortened, though it was never allowed to be under one minute. The reduction of that interval, however, makes the determination of oxygen-consumption, etc., on the highest loads less reliable than those on more moderate rates of work, a feature which receives further consideration below.

After making a series of measurements with the man breathing air, an exactly similar series was made when breathing oxygen. Before commencing the latter the subject was required to breathe oxygen for at least ten minutes to expel the greater part of the nitrogen dissolved in the blood. The interval between the air and oxygen tests was usually some hours; on several occasions the two series were carried out on different days. In the cases of several of those tested at the College, and of nearly all those tried at the Test Station, no information was given to the subject as to whether he was breathing oxygen or air. It was thought best not to give a loophole for the prejudice, which is still curiously strong, against breathing oxygen for a few hours.

After a few tests with a simple pneumograph it was abandoned. As has been stated, the rate of breathing was ascertained by watching the pointer of the meter on the inspiration side, and as the meter had its back to the subject he was generally unaware that any notice was being taken of his breathing.

**Ergometer Tests.**

Figs. 3 to 14 (see end of this Paper) are typical graphed records of subjects undertaking work on the ergometer in the manner described. The small circles on the charts indicate values obtained when the men were breathing normal air and the crosses those obtained when breathing oxygen; the more-or-less smoothed "air" curves are drawn in full lines and the "oxygen" curves in dotted lines. The output of CO₂ and the oxygen consumption are set out in litres per minute of dry gas at N.T.P. The volume ventilating the lungs is given in litres of saturated air or oxygen at blood temperature and normal pressure, expired per minute. The oxygen consumed was computed from the respiratory quotient and the CO₂ output.

The determination of the R.Q. by gas-analysis depends on the assumption that the mass of nitrogen inhaled is the same as the mass
of nitrogen exhaled. The nitrogen, in fact, serves here as a measure or standard against which variations in oxygen are gauged. Evidently such a process will be more accurate when the nitrogen, as in ordinary air, exceeds the oxygen in volume: i.e. when the smaller is gauged by the greater. It will be less accurate when the nitrogen proportion is much lower than that of oxygen, as when cylinder oxygen is breathed, for then the greater is gauged by the lesser. As might therefore be expected, oxygen consumptions, calculated in the manner indicated, from measurements made when breathing cylinder oxygen, had a relatively high probable error. Another method of evaluating oxygen consumption was, however, applicable, owing to the volumes inhaled and exhaled being separately measured; and in case of doubt this second method was used as a check. It consists of finding (a) the volume of oxygen entering the lungs per minute (from the volume of enriched air inhaled and the proportion of oxygen in that inhaled gas); (b) the volume of oxygen leaving the lungs per minute (from the volume expired per minute and the proportion of oxygen in the expired air), when the difference $(a) - (b)$ gives the required result.

Towards the end of the main series of experiments it was found that, even in a subject of low fitness, no advantage was to be secured by increasing the percentage of oxygen above 60. Had that fact been known earlier, the work would have been facilitated by using a mixture containing 60 p.c. oxygen and 40 p.c. nitrogen in place of cylinder oxygen; the higher proportion of nitrogen which would then have been available would have reduced the probable error of the oxygen consumption determinations on enriched air. At the Physical Test Station 67 p.c. of oxygen was used instead of cylinder oxygen.

It has sometimes been advanced as a drawback to the Douglas method that the sample of exhaled air collected in the bag is obtained over too short a period. For work of the character now being considered, however, the criticism would not appear to have much weight. If elementary precautions are taken, such as that of opening and closing the bag at the same stage in the breathing (e.g. at the end of inspiration), the shortness of the period of collecting the expired air is not a matter of consequence; of much greater importance is the length of the preliminary period during which the man is required to work before the expired air is allowed to enter the bag. This should be uniform and adequate.

It was not practicable to put the subjects on a definite dietary. While this increased the degree of uncertainty of any single pair of
observations it does not affect the general results, since a large number of men were tested, and whenever doubt was felt in regard to the reliability of a set of measurements the test was repeated on another day.

Normal and overload. Every-day experience proves that a muscular performance is easier when one is in "good condition." Equally commonplace are the facts that no task involving external work, not even the lightest, can be continued indefinitely without pause, and that the heavier the work the shorter the time it can be sustained. There are, however, certain lesser degrees of exertion (for instance walking or cycling at a moderate pace on a flat road) which, by the ease with which they can be kept up for hours on end, may be referred to, in electrical engineers' phraseology as "normal loads"; while other and heavier tasks (e.g. hard bayonet exercise or running quickly upstairs) are bearable for a limited period only and may be termed "overloads." What may be an overload to one person is a normal load to another who is stronger, or who is in better training or more habituated to the particular kind of labour. Again, a normal load when a person is fit may prove to be an overload when he is unfit; and, as has been remarked, even a light normal load if long supported without rest will eventually become an overload. Evidently, then, the whereabouts of the line demarcating between a normal and an overload for any individual depends on his condition at the time; if he is getting tired, it is moving down the scale of exertion; if resting, it is moving up.

Oxygen supply and carbon dioxide output during work. An important difference between what we here term the normal load and the overload lies in their effect on the respiration after stopping the exertion. When one ceases an easy normal load like walking at 3 m.p.h. along a flat road, the breathing quickly adjusts itself to the resting state: the after-effect in a healthy person is nil. The influence of a severe overload is in marked contrast to this; when the work is stopped heavy breathing continues; the lung-ventilation falls to normal only after a period which, in the case of a hard spell of work, may be many hours. In the first instance the oxygen intake was adequate; in the second it was not. Essentially, then, a normal load may be defined as one during the performance of which the oxygen supply is sufficient, and an overload one during which it is insufficient to satisfy in full the demands of the working muscles.

It is obvious that the supply of oxygen to the tissues may be deficient either in consequence of insufficient absorption in the lungs or inadequate circulation. Instances in which distress is produced by the rate of
oxygenation of the blood failing to keep pace with the muscular demands, though the circulation may be sufficient, are of great practical interest. They include the case of the poison-gas patient, where exudation and thickening of the epithelial layer of the lungs make oxygen-penetration difficult; the case of the high-flying airman, where the low partial pressure of oxygen prevents proper oxygenation of the blood, and that of the so-called D.A.H. patient, where the shallowness of the breathing impairs the transfer of oxygen to the blood by insufficient exposure of epithelial area to freshly indrawn air(6).

A glance at the accompanying charts will show that when hard muscular work is being done the consumption of oxygen may rise to more than ten times the resting value. In the muscles at work there must be a much greater proportional increase of consumption, and such an increase can only be secured by an enormous addition to the blood circulation through those muscles. Failure to supply the additional blood, whether due to defects in blood-distribution or to cardiac efficiency, must, therefore, bring about local anoxemia in the muscles, resulting in a cessation or reduction of the exertion.

Now it is known that, when muscles are insufficiently supplied with oxygen, lactic acid is formed; indeed that when an extreme overload is attempted, such as running quickly up several flights of stairs, the blood is at once flooded with lactic acid. The highly stimulative influence of lactic acid upon the respiratory centre and the relatively slow rate at which it disappears from the blood are also well known. The formation of this acid would therefore appear sufficient to account for the falling off of the percentage of CO₂ in the expired air which (as the curves show) is the invariable rule when the load is increased beyond a certain amount, and would also partly explain the long-continued enhanced breathing after the cessation of a heavy overload.

Since the appearance of lactic acid in the blood is a sure sign of overload, and since that appearance is characterised by a fall in the proportion of CO₂ expired, the writer feels justified in taking the rate of work corresponding to the maximal CO₂ proportion in the expired air as the boundary between an overload and a normal load, while breathing air or oxygen as the case may be. This boundary, it will be understood, can only be a rough one. Nor is it a stable one; fatigue moves it downward the scale. Again, the fact that in most cases (e.g. Fig. 4) the expired CO₂-percentage curve gradually flattens as the crest of the dome is approached, appears to denote the onset of oxygen-want before the "crest-load" is reached; but since that influence (except in the immediate
region of the crest load) is not usually serious, the subject can support such rates of exertion for a considerable time. In other words, though there is in the charts good evidence that the call for oxygen by the working muscles becomes (either per se or through the agency of lactic acid) a partner in respiratory control even on relatively light exertion, the demand appears to be satisfactorily met until the rate of work is increased up to, or nearly up to, what is here termed the "crest load."

Stamina. Stamina is taken to mean the power of supporting continuous exertion. It will be apparent that the higher the "crest load" the larger will be the range of loads which can be dealt with without oxygen-want bringing the exercise to an end. A given rate of work may be a normal load to one man whose "crest load" is high and an overload to another whose "crest load" is low. Thus the crest load (the abscissal position of the crest of the dome of the exhaled-CO₂-percentage curve) becomes a measure of the stamina for the particular kind of work in question.

In every case but one (Subject VIII) the crest load was higher (i.e. the crest was further to the right) when breathing oxygen than when breathing air. In most cases, that is to say, the boundary between normal and overload moves up the scale, and the subject's capacity for sustained exertion is improved, as the partial pressure of oxygen in the inhaled air, and, therefore, in the alveolar air, is increased. The lower the person's fitness the greater the improvement brought about.

Alveolar CO₂ during the accelerative period. As has already been stated, a rate of work like 12,000 ft. lbs. per min. was too heavy to be kept up long by any of the men tested, and on such loads it was not possible to wait the usual two minutes before taking the samples and readings. The result was that on the heaviest loads, the latter were taken during the accelerative period. In some instances (Subjects II, III, IX, XIII, XV) alveolar samples were obtained during that period, and the CO₂-percentages are shown on the graphs. They will be seen to be unusually high; indeed with Subject XIII, breathing air, the record figure of 10-1 p.c. is reached. The matter lay outside the scope of the research and was not pursued further; but it would seem questionable whether these high CO₂ tensions are possible in the alveolar air without active excretion of CO₂ on the part of the lung-epithelium.

Fitness and expired-CO₂-percentage. The graphs may now be examined with a view to ascertaining the influence of fitness on respiratory behaviour.

The high level of the CO₂-percentage in the air expired by most fit
persons doing work is perhaps the first feature to attract attention. It is a usual but not an invariable attribute of the fit man that he can stand a higher CO₂ and a lower oxygen percentage in the alveolar air than the unfit man performing the same task; he makes more use of the air he inhaled and therefore requires less of it. Thus, in contrasting the very striking athletic subject XIII (condition (A), Fig. 10) with the sedentary subject II (Fig. 4) when both are breathing normal air, the maximal CO₂ percentage in the former case is seen to be 8.1 and in the latter case 4.7, and, although the heavier man, XIII can work the ergometer on a lung-ventilation of less than half that required by II. The highest CO₂ and lowest oxygen proportions were recorded in the case of those to whom slow, deep breathing is habitual during physical exercise. While working at the rate of 6000 ft. lbs. per min., for example, II breathed 24 times per min., while two unusually deep breathers, Nos. XIII and VIII, respired 8 times and 12 times per min. respectively on that load. That the correspondence of high fitness and a high CO₂ level is not invariable is shown by a subject (graphs not reproduced), a very fit young athlete, whose expired-CO₂-percentage reached a maximum of only 4.8 when breathing oxygen.

Fitness measurement. Perhaps the most interesting and useful of the results obtained follows from a comparison of the curves of exhaled-CO₂-percentage when the subject breathes air and when the subject breathes oxygen. In the case of a relatively unfit man, such as II, these curves diverge; but in that of VIII (Fig. 8)—an army instructor in physical drill selected for experiment by the Scottish Command as representing physically the best the Army can produce—the curves are almost coincident and their crests actually coincide. Observations on many subjects have warranted the conclusion that fitness is inversely as the degree of divergence of the two CO₂ curves. The most convenient manner of evaluating fitness proved to be the following: having drawn the two contrasting curves (work done, abscissæ; CO₂ percentages, ordinates) the expired-CO₂-percentage, with the subject at rest and breathing normal air, was marked by an arrow-head on the Y-axis of the graph. A horizontal line having then been struck across the chart through the arrow-head, the vertical distances between that line and the crests of the “air” and “oxygen” curves were measured off. The fitness factor was then taken to be the first of these distances divided by the second. By this method the fitness of Subject II was 46 p.c. and that of VIII was 100 p.c. The factors for the other selected subjects are stated in the Appendix (p. 311).
The assumption underlying this mode of expressing fitness is two-fold: first, there is, as basis, the conception of zero fitness as being the state in which the CO₂-curve on air falls away from the Y-axis, or, in other words, in which the crest lies on that axis at a point coincident with the resting value of the CO₂-percentage. That is to say, zero fitness is regarded as the condition in which the slightest load is an overload and where oxygen want becomes serious when the least exertion is attempted. Secondly, there is the assumption that breathing oxygen raises fitness (as regards the lungs) to 100 p.c. The first point will be readily conceded; as to the second, the evidence appears conclusive. Subject III was tested on occasions several months apart; the first time he was in low health and his fitness factor was 44 p.c.; the second time he was well and the factor had risen to 80 p.c.; but the CO₂ curve on oxygen was substantially the same in each case. Subject XIII was frequently tested over a period of six months. At first he was in normal health and had a fitness of 70 p.c. He was then sent to Aldershot for the final course of training for sergeant-instructors in physical drill and returned to Edinburgh, in the “pink” of condition, for further test after being a fortnight at Aldershot. It was then found that while the “oxygen” curve was substantially as before, the “air” curve had risen to meet it, and that, indeed, the two curves agreed up to the crest. In other words, fitness had become 100 p.c. Some time after, XIII was transferred back to Scotland under medical orders; he had become very “stale” and run down. He was again tested and found to have a fitness of 55 p.c.; but, as before, the change was evidenced by a movement of the “air” curve only.

It is to be observed from the results that, when an overload is being dealt with, even the fittest men derive some assistance from breathing enriched air, while the unfit benefit to a still greater extent. An overload to a relatively unfit person breathing ordinary air may become a normal load when he breathes, say, 70 p.c. oxygen. A man getting fatigued while supporting what was at first a normal load but which has now become an overload, no matter how fit he may be, is relieved by breathing enriched air,—an effect which has been remarked by other observers. Conversely, heavy work can be accomplished with less fatigue when respiring oxygenated air continuously from the commencement.

The method of measuring fitness described above involves the assumption that lung-fitness indicates general physical fitness. Such appears actually to be the case if an exception be allowed in the instance of persons inured to living at a high altitude; in those circumstances the
required degree of adaptation is not derived so much from physical exercise as from long-continued exposure to low oxygen pressure, and the lungs may be highly efficient without general bodily fitness being a necessary consequence.

_Bearing on the oxygen secretion question._ Since an unfit man derives much benefit during muscular exertion through addition of oxygen to the inspired air, while a fit man is very little benefited, it seems clear that the lungs of the fit man absorb oxygen more readily from normal alveolar air during exertion. This might be due either to some anatomical change which makes simple diffusion occur more readily through the lung epithelium of the fit man, or to active secretion of oxygen inwards by the lung epithelium.

The former theory does not seem inherently probable; but if it were correct we might expect that even during rest the alveolar CO₂-percentage would be higher among fit than among unfit men. To ascertain whether this is so the records of 84 men were examined. They were of every medical category, though the "A" class preponderated. Their ages ranged from 15 to 50, though most were of the usual military age. The following table sets forth the expired-CO₂-percentage sitting at rest against the fitness factor, the latter having been determined as described above:

<table>
<thead>
<tr>
<th>Fitness p.c.</th>
<th>Number of subjects examined</th>
<th>Average expired-CO₂ p.c. at rest</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-50</td>
<td>6</td>
<td>3.52</td>
</tr>
<tr>
<td>50-60</td>
<td>10</td>
<td>3.75</td>
</tr>
<tr>
<td>60-70</td>
<td>23</td>
<td>3.66</td>
</tr>
<tr>
<td>70-80</td>
<td>19</td>
<td>3.61</td>
</tr>
<tr>
<td>80-90</td>
<td>20</td>
<td>3.52</td>
</tr>
<tr>
<td>90-100</td>
<td>6</td>
<td>3.60</td>
</tr>
</tbody>
</table>

The evidence is emphatically negative; the expired-CO₂-percentage at rest, and therefore, by inference the oxygen tension of the alveolar air at rest, is not affected by a very large variation in fitness.

The secretion theory as propounded by Bohr and by Haldane and his co-workers affords a more probable explanation. The theory predicates that the epithelial cells possess the power, which they exercise in response to stimuli originating in anoxemia of the tissues, of secreting oxygen from the alveolar air into the blood(7). When a person is at rest he gets oxygen by simple diffusion; but during work, or during existence at a high altitude, the amount so obtained is inadequate and is supplemented, as shown by the experimental data of these observers, by secretion.
Once these cells are regarded, so to speak, as oxygen pumps which can be set going when required, the experimental results described above become intelligible. Practice or training facilitates the oxygenation of the blood by improving the cells' power of secretion. In the fittest men, no benefit is derived during normal load from breathing enriched air, since they are able to get from normal air by secretion all the oxygen they need. The existence, in the lung epithelium, of a capacity which can be developed and intensified by training or other means of adaptation and which inferentially may be impaired by overwork or overstrain, throws a new light on the phenomena of respiratory fatigue.

Oxygen consumption. Table II, which has been drawn up from the smoothed curves, gives, in litres per minute of dry gas at N.P.T., the oxygen consumption of the selected subjects while doing work on the ergometer and while breathing both normal air and oxygen.

**Table II. Oxygen Consumption. Ergometer experiments.**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Breathing air</th>
<th>Breathing O₂</th>
<th>Sitting at rest</th>
<th>3000</th>
<th>6000</th>
<th>9000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>0.31</td>
<td>1.23</td>
<td>1.65</td>
<td>1.77</td>
<td>2.42</td>
</tr>
<tr>
<td>II</td>
<td>0.23</td>
<td>0.31</td>
<td>1.23</td>
<td>1.20</td>
<td>2.08</td>
<td>2.42</td>
</tr>
<tr>
<td>III</td>
<td>0.37</td>
<td>0.22</td>
<td>1.03</td>
<td>0.81</td>
<td>2.62</td>
<td>2.20</td>
</tr>
<tr>
<td>IV</td>
<td>0.33</td>
<td>0.28</td>
<td>1.12</td>
<td>0.95</td>
<td>1.68</td>
<td>2.04</td>
</tr>
<tr>
<td>V</td>
<td>0.28</td>
<td>0.37</td>
<td>1.17</td>
<td>0.81</td>
<td>1.80</td>
<td>1.44</td>
</tr>
<tr>
<td>VI</td>
<td>0.47</td>
<td>0.40</td>
<td>1.17</td>
<td>1.02</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>VII</td>
<td>0.45</td>
<td>0.40</td>
<td>1.13</td>
<td>1.05</td>
<td>1.70</td>
<td>2.37</td>
</tr>
<tr>
<td>VIII</td>
<td>0.42</td>
<td>0.32</td>
<td>1.05</td>
<td>0.97</td>
<td>1.58</td>
<td>2.27</td>
</tr>
<tr>
<td>IX</td>
<td>0.40</td>
<td>0.30</td>
<td>1.00</td>
<td>1.05</td>
<td>1.68</td>
<td>2.30</td>
</tr>
<tr>
<td>X</td>
<td>0.37</td>
<td>0.28</td>
<td>1.12</td>
<td>0.81</td>
<td>1.83</td>
<td>2.32</td>
</tr>
<tr>
<td>XII</td>
<td>0.40</td>
<td>0.31</td>
<td>1.07</td>
<td>0.92</td>
<td>1.88</td>
<td>2.04</td>
</tr>
<tr>
<td>XIII(a)</td>
<td>0.33</td>
<td>0.25</td>
<td>0.70</td>
<td>0.93</td>
<td>1.47</td>
<td>1.75</td>
</tr>
<tr>
<td>XIII(b)</td>
<td>0.37</td>
<td>0.25</td>
<td>1.30</td>
<td>1.65</td>
<td>2.00</td>
<td>2.65</td>
</tr>
<tr>
<td>XIV</td>
<td>0.38</td>
<td>0.25</td>
<td>1.17</td>
<td>0.92</td>
<td>2.00</td>
<td>2.62</td>
</tr>
<tr>
<td>XV</td>
<td>0.25</td>
<td>0.35</td>
<td>1.07</td>
<td>0.98</td>
<td>1.83</td>
<td>2.80</td>
</tr>
<tr>
<td>XVIII</td>
<td>0.42</td>
<td>0.24</td>
<td>1.30</td>
<td>1.00</td>
<td>2.00</td>
<td>2.71</td>
</tr>
</tbody>
</table>

**Average** 0.36 0.32 1.12 0.97 1.74 1.54 2.33 2.16

Efficiency of Ergometer Work. The curves relating to efficiency at different loads have a certain interest, though of all the results these are perhaps most open to criticism and require most qualification. They were computed from the oxygen consumptions and from Zuntz's table of energy-equivalents.(8) They are "gross" or "overall" efficiencies and give, at different loads, the relation between the useful external work done by the human machine and the energy generated within that machine by exothermic chemical changes. A person pedalling the ergometer with the belt off and thus doing no external work
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has, on this basis, zero efficiency. The accuracy of these estimates depends on several factors. The manner of arriving at Zuntz's figures has, the writer believes, been considerably criticised, though in view of the other sources of error now to be noted small imperfections in those values are barely worth considering. The evaluation of efficiency on normal load is comparatively straightforward and probably fairly exact, but grave difficulties arise when overloads are being dealt with. Being determined from the oxygen consumption, an efficiency is evidently affected by error in measuring the oxygen consumed. Further it is important to realise that, as a statement of the rate of oxygen consumption at a given time, say two minutes after starting an overload, a certain value may be accurate and yet it may yield altogether misleading results if used as the basis for calculating efficiency at the same time. This conclusion follows from the fact that to measure efficiency accurately there must be a correct correlation of energy intake and energy-output. There is, however, no such agreement during an overload when the output of energy is, for a time, excessive. The portions of the curves which are considered unreliable for this reason are shown by even dots.

If efficiency had been the subject under study, it would have been necessary to endeavour to correct the curves by taking into account the excess oxygen consumption during the post-work period. An interesting feature (which has been noted by previous workers) becomes apparent when an efficiency curve is corrected in that manner; it is then seen to be dome-shaped: in other words, as the load increases the efficiency reaches a maximum and then falls away again. The maximum occurs at or near the line of demarcation of normal load and overload. Even with the uncorrected efficiencies graphed, the tendency towards the domed form can be detected in several cases, as for example in that of Subject IX. Zuntz's values being based upon the respiratory quotient, the abnormality of the R.Q. during severe work is another disturbing factor.

Generally speaking, the efficiency appears to be greater when breathing oxygen than when breathing air. With the relatively unfit person that effect may be partly due to the fact that, for a given load, less energy is consumed in respiration when breathing oxygen. The efficiency of the fit is greater than that of the unfit man. This again may to some extent be owing to the relatively small respiratory effort of the fit person; but no doubt the fact of the fit man being usually habituated to physical exertion, and having learnt to deal with a tas
with a minimum waste of muscular energy as possible, has a great deal to do with his higher efficiency. For example, the expenditure of energy and consumption of oxygen involved when a miner uses a shovel are markedly less than when the same task is performed by a person unaccustomed to shovelling.

Climbing and Walking Experiments.

A number of experiments were made on men climbing the main incline of the Burdiehouse limestone mine, Midlothian, both while breathing normal air and while breathing oxygen. Preliminary tests in the Lingerwood and Newbattle Collieries had shown the advisability of limiting the variables. This could be done either by taking one subject on a number of gradients or by taking several subjects on one gradient, and the latter alternative was chosen as being likely to give most information. The Burdiehouse incline lies at a uniform slope of 21°. The roof is high, so that there was no occasion to stoop, and the floor, while dry for the most part, was, at the time of the tests, wet and slippery in places. On the whole the condition of the incline might be taken as a fair average of that of a mine roadway of heavy grade. Owing to the difficulties encountered in fitting up, each day, a temporary laboratory on the side of the roadway, I had to be satisfied with a few determinations for each man; usually values were obtained at five rates of speed, both when breathing air and when breathing oxygen.

It was intended to put the results, especially as to oxygen consumption, in the most useful form for designers and users of mine rescue apparatus; therefore the subject carried such an apparatus both during the climbing tests and during the walking and running trials on the flat which are referred to below. The total weight borne on each occasion was about 43 lbs. The values thus apply to fully-equipped infantrymen. The procedure during these experiments was the following:

Breathing normal air. The subject carried a Douglas bag on his back and an exhalation bag, fitted with a relief valve, on his chest. He breathed through a mouthpiece, his nose being clipped. Inhalation and exhalation valves were so placed that he drew air from the Douglas bag and expired into the exhalation bag. Before starting, the Douglas bag was inflated with a measured volume of air by aid of a large double-acting bellows. The man was then set to walk up the incline (which was marked off in chains and poles) at the desired rate. The 3-way tap of the Douglas bag being "off," he inspired, at first, from the atmosphere.
When it was judged that his respiration had adjusted itself to the degree of exertion, the 3-way tap was turned "on" and he began to breathe from the measured volume in the Douglas bag. The length of the spell of work, from the moment of turning on the tap to the moment of turning it off again, was taken by a stop-watch. After the spell samples for analysis were withdrawn, over mercury, from the exhalation bag, and the volume remaining in the Douglas bag was metered.

**Breathing oxygen.** Before any observations were made on oxygen, the man was required to use the mine rescue apparatus which he was carrying for a sufficient time to remove the bulk of the free nitrogen dissolved in the blood and tissues. During this preliminary period the nitrogen percentage in the air of the closed circuit of the apparatus was kept low by frequently washing out through the relief valve with excess oxygen. After that operation the subject was not allowed to breathe ordinary air until the whole of the oxygen series of tests was completed.

During rests, and during the first part of a climb while the respiration was accelerating, he used the rescue apparatus. The routine was the same as that described above, the Douglas bag, however, being filled with a measured volume of oxygen, and the subject, on the word of command, changing rapidly from the rescue apparatus mouthpiece to that of the respiration apparatus, or vice versa.

The walking and running tests were made on a smooth, level concrete track at the Mine Rescue Station, Edinburgh.

The results of two such tests are set forth in Figs. 12 and 13. Fig. 14 is constructed from information relating to "C.G.D." and obtained from a paper by Haldane and Douglas(9); it is included for the sake of comparison. In condition (a), indicated on the graph by full lines this subject was breathing normal air and walking on the laboratory floor, while in condition (b), indicated by chain dots, he was breathing air and walking in a level grass field. He did not carry a load; therefore the consumption of oxygen and production of carbon dioxide are relatively less than those of the other subjects. Though the figures actually obtained in Haldane and Douglas’ experiments were used in drawing the graphs, 25 p.c. has been added to "C.G.D.’s" oxygen consumption in the following table to make them more comparable with those of the other men, who were carrying 43 lbs. each.

Tables III, IV and V, derived from the smoothed curves, state oxygen consumptions (expressed in litres per minute of dry gas at N.T.P.) of men walking and running on the flat and climbing the Burdiehouse incline:
TABLE III. Oxygen Consumption. Walking and running on the flat, carrying weight of 43 lbs.

<table>
<thead>
<tr>
<th>Miles per hour</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.71</td>
<td>0.68</td>
<td>0.77</td>
<td>0.85</td>
<td>0.80</td>
</tr>
<tr>
<td>II</td>
<td>0.47</td>
<td>0.53</td>
<td>0.59</td>
<td>0.80</td>
<td>0.74</td>
</tr>
<tr>
<td>III</td>
<td>0.25</td>
<td>0.41</td>
<td>0.47</td>
<td>0.90</td>
<td>0.70</td>
</tr>
<tr>
<td>XII</td>
<td>0.31</td>
<td>0.28</td>
<td>0.60</td>
<td>0.88</td>
<td>1.00</td>
</tr>
<tr>
<td>XVI</td>
<td>0.55</td>
<td>0.57</td>
<td>0.70</td>
<td>0.92</td>
<td>1.22</td>
</tr>
<tr>
<td>Average</td>
<td>0.71</td>
<td>0.68</td>
<td>0.77</td>
<td>0.91</td>
<td>0.85</td>
</tr>
</tbody>
</table>

C.G.D.(a) | 0.40 | 0.71 | 0.68 | 0.77 | 0.91 | 0.85 | 1.40 | 2.22 | 3.00 | 2.80 |

(b) | 0.40 | 0.71 | 0.68 | 0.77 | 0.91 | 0.85 | 1.40 | 2.22 | 3.00 | 2.80 |

* Unusually high: omitted in averaging.
† Interpolated from the graph.

TABLE IV. Oxygen Consumption. Climbing mine incline of 21°, carrying 43 lbs.

<table>
<thead>
<tr>
<th>Work done in foot-pounds per minute</th>
<th>3000</th>
<th>6000</th>
<th>9000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Br. air</td>
<td>0.62</td>
<td>0.60</td>
<td>0.46</td>
</tr>
<tr>
<td>Br. oxygen</td>
<td>0.57</td>
<td>0.51</td>
<td>0.46</td>
</tr>
<tr>
<td>Breathing air</td>
<td>1.08</td>
<td>1.47</td>
<td>1.20</td>
</tr>
<tr>
<td>Breathing oxygen</td>
<td>1.37</td>
<td>1.47</td>
<td>1.23</td>
</tr>
<tr>
<td>Breathing air</td>
<td>2.02</td>
<td>2.17</td>
<td>2.20</td>
</tr>
<tr>
<td>Breathing oxygen</td>
<td>3.10</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Average</td>
<td>1.20</td>
<td>1.23</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Most economical rate of walking. Like a steamboat or an airship, a man has a most economical speed at which he goes furthest per litre of oxygen or per pound of fuel or food consumed. The data obtained yield the following information: "C.G.D.'s" most economical speed while breathing air and walking without burden on the laboratory floor, was...
four miles per hour, at which rate he moved 99 yards per litre of oxygen consumed. Walking without burden on grass, the same subject's most economical speed was three miles per hour, when a litre carried him 82 yards. With all the other subjects of Table III—loaded, as each of them was, with 43 lbs.—the most economical speed proved to be three miles per hour when breathing air, while, when breathing oxygen and similarly loaded, that rate was three miles per hour for I, II and III, and four miles per hour for XIII and XVI. It is apparent that increased difficulty of walking, whether due to the man carrying a weight or to lack of smoothness of the path, reduces the most economical speed.

The writer expresses his obligation and gratitude to Dr J. S. Haldane for the encouraging interest he took in these experiments and for his equally invigorating criticism. Mention must also be made of the loyal assistance given by Miss Elizabeth Gilchrist, M.A., B.Sc., and Mr David Penman, B.Sc., in conducting the experiments; of the painstaking work of the Physical Test Station Staff, and of the very willing help given by a great many mine officials, miners, soldiers, and others in the course of tests which were often of an arduous nature.

**SUMMARY.**

1. Physical work is found by experience to be easier to unfit men when oxygenated air is breathed than when normal air is breathed, but no such difference is to be observed with fit men.

2. When exertion of steadily increasing magnitude is undertaken, the expired-CO$_2$-percentage first rises and then falls. The load at which that percentage is a maximum is called the "crest load." It is shown that the crest load demarcates between normal loads and overloads. The demarcation line is not constant, and the circumstances causing movement of that line are discussed.

3. If curves be drawn showing work done (abscissae) and exhaled-CO$_2$-percentage (ordinates), (a) when the subject breathes air, and (b) when he breathes oxygen, the curves are found to coincide up to the crest where the man is very fit and to diverge widely when he is unfit, since the CO$_2$-percentage becomes much lower in the unfit when only ordinary air is breathed. A method of measuring fitness is described; it is based upon the experimental fact that fitness is inversely as the divergence of these curves.
(4) On an overload, even the fittest man derives benefit from breathing enriched air.

(5) The nature of the adaptation produced by physical training and by certain vocations is compared with that found to result from living at a high altitude. The bearing of the results upon the oxygen secretion question is considered and reasons are given for the acceptance of the secretion hypothesis.

(6) The benefit of breathing enriched air when doing physical work is limited to air containing about 60 p.c. oxygen. Enrichment above that proportion has no effect during exertion, even on very unfit persons.

(7) Tables are inserted setting forth the oxygen consumptions of numerous subjects while working the ergometer, while walking and running on the flat, and while climbing a mine incline of 21° slope, and the most economical rates of walking are shown for several subjects.

APPENDIX. Description of subjects selected for illustration.

Subject I (Fig. 3). Miner (repairer) working in steep seams; weight, 154 lbs.; fitness 83 p.c.; the position of the “peak load” (7500–8000 ft. lbs. per min.) is higher than the average, indicating a man of good stamina.

Subject II (Fig. 4). Sedentary person; weight, 136 lbs.; fitness 46 p.c.; finds work much easier when breathing oxygen; oxygen-want apparent at relatively low rates of exertion.

Subject III (Fig. 5). Instructor at a mine rescue station; weight, 165 lbs.; fitness 80 p.c.

Subject IV (Fig. 6). Mine undermanager; weight, 168 lbs.; engaged in a mine working flat seams; fitness, 64 p.c.; oxygen-want becomes serious under 6000 ft. lbs. per min.

Subject VI (Fig. 7). Army recruit; previously a bank clerk; weight, 142 lbs.; fitness, 42 p.c.

Subject VIII (Fig. 8). Regular soldier; weight, 168 lbs.; instructor in physical drill; heavy weight lifter; athletic type; fitness, 100 p.c. Judging from his general behaviour while doing work (quite apart from the results obtained) he is the fittest man of the series. Breathing oxygen is not the least benefit until the crest load is exceeded; then it gives a gradually increasing assistance.
Subject IX (Fig. 9). Mine fireman or deputy, working in a flat-seam colliery; weight, 168 lbs.; fitness, 69 p.c.

Subject XIII (Fig. 10). First-class footballer; runner, jumper and all-round athlete; Army instructor in physical drill; weight, 158 lbs. Records were obtained of the subject in three conditions: (1) in good health; fitness, 70 p.c. (the ergometer results labelled (A) were obtained on that occasion); (2) in good health and after intensive training at Aldershot; fitness, 100 p.c.; and (3) in poor health; fitness, 55 p.c. The ergometer tests marked (B) and the climbing and walking tests were carried out with the man in the last condition. The low rate of breathing, small lung-ventilation, great depth of breathing and abnormally high CO₂-percentage level are remarkable features.

Subject XV (Fig. 11). Assistant instructor at a mine rescue station; weight, 147 lbs.; fitness, 63 p.c.

Subject XVI (Figs. 12, 13). Research assistant, sedentary habits; weight, 154 lbs.

C. G. D. (see p. 308), Fig. 14.

REFERENCES.

(3) Haldane and Priestley. This Journ. 32, p. 225. 1905.
(6) Haldane, Meakins, and Priestley. This Journ. 52, p. 433. 1919.
(9) Douglas and Haldane. This Journ. 45, p. 235. 1912.
FITNESS AND BREATHING

SUBJECT I

FIG. 3

SUBJECT II

FIG. 4
Figure 5

Subject III

Figure 6

Subject IV
FITNESS AND BREATHING

SUBJECT I

SUBJECT II

FOOT-POUNDS

PER MINUTE

3000

6000

9000

12000

PERCENT CARBON-DIOXIDE EXHALED

LITRES EXHALED PER MINUTE

BREATHS PER MINUTE

PERCENT CARBON-DIOXIDE EXHALED

LITRES EXPIRED PER MINUTE

BREATHS PER MINUTE

3000

6000

9000

12000

LITRES OXYGEN CONSUMED PER MINUTE

LITRES CO₂ EXHALED PER MINUTE

EFFICIENCY
FIG. 9

SUBJECT IX

FIG. 10

SUBJECT XIII

REST

FOOT-POUNDS PER MINUTE
0 3000 6000 9000 12000

PERCENT CARBON DIOXIDE CERATED

FOOT-POUNDS PER MINUTE
0 3000 6000 9000 12000

FOOT-POUNDS

3000 6000 9000 12000

PERCENT CARBON DIOXIDE CERATED

FOOT-POUNDS PER MINUTE
0 3000 6000 9000 12000

FOOT-POUNDS PER MINUTE
0 3000 6000 9000 12000
FIGURE 11

SUBJECT XV

FIGURE 12

SUBJECT XVI
SUBJECT XVI

FIG. 13

FIG. 14

SUBJECT - C.G.D.
(BREATHING AIR ONLY)

WALKING ON LAB FLOOR
WALKING IN GRASS

WALKER CO. PERCENT
PERCENT CO. IN EXPIRED AIR
Physical Work and the Human Machine
PHYSICAL WORK AND THE HUMAN MACHINE.

A PAPER READ BEFORE
THE MINING INSTITUTE OF SCOTLAND.

BY

PROF. HENRY BRIGGS, D.Sc.

GENERAL MEETING AT EDINBURGH,
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PHYSICAL WORK AND THE HUMAN MACHINE.

By Prof. Henry Briggs, D.Sc.
ENGINEERS have devoted the most painstaking attention to all the prime-movers used in general practice, except one. That exception is the human machine, the most ubiquitous, complex, delicate, expensive, and troublesome of all. Our very familiarity with that engine, and the knowledge which each of us possesses of its possibilities and of certain of its limitations, probably account to a large extent for the engineer's neglect of its study. The engineer, indeed, has been content to leave the matter entirely to the physiologist: he has not been willing to trespass on what he regarded as foreign ground. This view I now challenge, as I see no reason for barbed-wire fences between the sciences, and believe that an occasional venture across the border is stimulating to both sides. It is, for example, impossible to exaggerate the benefit mining has gained from the "raids" of one eminent physiologist to whom frequent reference is made; we can, at any rate, make an attempt to repay him in kind by an excursion into physiology.

Let us begin by comparing the more obvious attributes of the human machine with those of a mechanical prime-mover, and, as we are here concerned solely with physical work and its consequences, let us disregard the intellectual and emotional capacity of the former.

In the first place, the human being is a complete portable plant capable of consuming fuel, of developing heat-energy by virtue of the chemical union of oxygen with the carbon and hydrogen of that fuel, and of converting a part of this heat-energy into mechanical energy. So far, there is parallelism with a plant consisting of a boiler and steam-engine. The likeness is increased by the means adopted to reduce heat-loss; in both cases lagging of non-conducting material is employed, although the human being chooses to speak of his detachable lagging as clothing. Here, however, the resemblance ends.

The first difference between the cases—and it is an important one—is in regard to the temperature at which the chemical action between the fuel and the oxygen goes on. In the animal that temperature is low, and it is fixed with such definiteness that if it be altered even a few degrees up or down the scale the organism is totally disabled. An effect of the relatively low temperature at which the vital processes go on is that the amount of clothing worn must be made to vary with the external temperature; and in hot, damp situations where physical work is proceeding, the need to expose as much uncovered skin as possible is so imperative that the nature of the clothing affects both the capacity for work and the safety of the worker. Too much lagging in such circumstances may wreck the machine.

In the engine-and-boiler plant oxygen is consumed only in the boiler-furnace, not in the engine; but in the animal oxidation goes on all over the system, and in particular in muscles which are doing physical work. In both cases air is drawn in and used up continuously, and the boiler is
feds with fuel more or less continuously; but a man takes in his fuel-supply at relatively long intervals, and finds it almost essential to cease work during the stoking operation. He has a great storage capacity for fuel, but very little indeed for oxygen. If need be, he can work for a long time after his food-supply is cut off; but he dies in a few minutes if the oxygen-supply is stopped.

A striking difference is to be observed when air containing a high percentage of oxygen is used in place of normal air. A furnace, if fed with such enriched air, would burn with greater intensity; it would consume a larger weight of coal per square foot of grate area, and would produce little if any smoke; the steam output of the boiler would be increased. Nothing comparable with this occurs when a man breathes oxygen or highly-enriched air. Notwithstanding the widely-diffused popular belief to the contrary, he does not become intoxicated; there are no paroxysms of uncontrollable energy followed by lassitude. If the air of this room were suddenly changed to pure oxygen of the same temperature and hygrometric state, not one of us would be the wiser. When a mine-rescue apparatus is used, for example, the air inhaled often holds 80 and sometimes 90 per cent. of oxygen, and there is no deleterious effect on the wearer on that score. In my experiments on this subject, I found that, instead of a more rapid consumption of tissue, the breathing of cylinder oxygen made no difference in that respect when the person was at rest, and actually resulted in a slightly reduced consumption when he was doing work on a bicycle dynamometer.

In other words, most people are a little more efficient as working machines when they respire enriched air. The human organism, then, takes what oxygen it needs from enriched air, and expires the remainder as though it were so much inert gas.

When a healthy man starts to do physical labour, the brain responds by accelerating the heart's speed and pressure of pumping, by dilating the arteries in and leading to the muscles doing the work, so as to increase the blood-circulation in those parts, and by enhancing the respiration (which is either deepened or quickened or both) in order to draw into the lungs the additional oxygen required. The extra supply of oxygen to the muscles at work is therefore derived, in the first place, from the passage of a greater amount of the gas per second from the air in the lungs into the blood, and, in the second place, from a more rapid transport of the oxygen, by the blood, from the lungs to the muscles. This question of the supply of oxygen to the muscles lies at the very root of the study of physical work. To make hard work possible, there must be an efficient co-operation of brain, heart, and lungs, in addition to a sufficient muscular development and sufficient nourishment.

Most of the writer's experiments were carried out with the ergometer of Prof. E. G. Martin. This is nothing more than a bicycle dynamometer, and consists of the frame, seat, pedals, and chain-drive of an ordinary bicycle supported on a wooden stand; the front wheel is absent, and in place of the back wheel there is a flywheel, round the rim of which passes a linen belt in the manner of the Prony brake. Adjustable strings are connected to the ends of the belt, and these in turn are attached to spring-balance. The gearing of the cycle is such that when the pedals are turned at 56 revolutions per minute the difference of the spring-balance readings multiplied by 1,000 gives the external work done in foot-pounds per minute. When a man is caused to do work on this machine, and his exhaled air is collected, metered, and analysed, certain
facts emerge.* It is seen, for instance, that the proportion of carbon dioxide in the expired breath is not constant; it is lowest at rest, and it rises as the rate of work increases until it reaches a maximum, and then, if still harder work be given, the proportion of carbon dioxide falls again. Thus, when set out on a graph (Curve A, Fig. 1, for example) the curve connecting exhaled-carbon-dioxide percentages (plotted as ordinates) and work done on the ergometer (abscissae) assumes a domed form.

It will be convenient to speak of the rate of work corresponding to the maximal carbon-dioxide percentage as the "crest load." The dipping of the curve beyond the crest load is a certain indication of want of oxygen: at such heavy rates of exertion the muscles do not receive all the oxygen they are calling for; they become partially asphyxiated, and the work soon has to be stopped or much reduced. Up to the crest load, on the other hand, the evidence is to the effect that oxygenation is sufficient, and rates of exertion below the crest load can be supported for a considerable time. Certain of the terminology of the electrical engineer is useful in this connexion. When an electric motor is generating mechanical power at the rate for which it was designed, we say that it is working at "full load"; any rate of energy-output below full load is termed a "normal load" for the motor; whilst if it be called upon to develop power in excess of the full-load, the excess is spoken of as "over-load." With the human machine, then, the crest load is full load; anything under the crest load is a normal load, and anything above it an over-load. Although the crest load demarcates between a normal and an over-load, it must not be thought that that boundary is a fixed one for any given person; it varies in position according to the man's health; fatigue also moves it down the scale of exertion, and a task that began as a normal load may become an over-load towards the end of a hard shift. The effect of age is to move the boundary permanently down the scale, as may be gathered from a comparison of the A curves of Subject P.T.S. 1/24 (Fig. 7) and Subject P.T.S. 1/41 (Fig. 6). The former subject is a well-developed athletic youth of 18 with a crest load of 11,000 foot-pounds per minute, and the latter a man of 45 with a crest load of only 2,500 foot-pounds per minute. If stamina be defined as the capacity for sustained exertion, it will be evident that the crest load provides a relative measure of a subject's stamina at the time of the test.

There are factors in mining which affect a man's capacity for exertion, and which are seldom met with in other occupations. For example, the underground worker may have to labour in air containing carbon dioxide and an excess of nitrogen. The presence of carbon dioxide is generally supposed to militate considerably against effectual physical work, but experiment indicates that its influence in this respect has been exaggerated. The addition of, say, 2 per cent. of carbon dioxide alone to air is not detrimental. Its effect, indeed, is to augment the depth of breathing, and thus to promote rather than impede the transfer of

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oxygen to the blood.* A large proportion, such as 5 or 6 per cent., added alone to air certainly reduces the crest load and the stamina, and

brings on headache and fatigue; but in the percentages met with in the general body of the air under present-day mining conditions nothing is

to be feared from carbon dioxide \textit{per se}. Unfortunately, it does not make its appearance unaccompanied in mine air; it is always associated with a much larger and variable amount of nitrogen. It is only in mine-rescue apparatus that we can deal with the gas as the only intruder in the air respired. Owing to it chiefly consisting of nitrogen, blackdamp in large proportion is generally more serious because of the diminution in oxygen which it causes than because of the carbon dioxide it contains. For those engaged in physical work it is more important that the percentage of oxygen in the air should not sink below 19 than that the carbon dioxide should not exceed \(1\frac{1}{2}\) per cent. It is a handicap to have to carry out long-continued work in an atmosphere containing 19 per cent. of oxygen; in all but exceptionally fit young men a drop of even 2 per cent. in the oxygen-proportion reduces the worker's stamina and promotes fatigue. The oxygen-percentage turns out to be so much the more important of the two standards of Section 29 (3) of the Coal Mines Act that, for practical purposes, the carbon-dioxide limit might have been omitted.

A second factor influencing the miner's capacity for work is the wet-bulb temperature of the air. When that temperature approaches that of the blood, the system becomes less able to prevent an increase of body-temperature by the evaporation of sweat on the skin, and physical exertion, if persisted in under such conditions, may lead to death from heat-stroke. Our knowledge of the limits of human endurance under high wet-bulb temperatures is largely due to Dr. J. S. Haldane. The following sentences are taken from the \textit{First Report of the Committee on "The Control of Atmospheric Conditions in Hot and Deep Mines"} \cite{Haldane1919}.

"... with the wet-bulb temperature at 78° continuous fairly hard work in still air was impossible. The wet-bulb temperature at which, with an air-current such as might be expected along a well-ventilated working-face, and an amount of work such as an average miner does, the normal body-temperature could be maintained, was not determined, and remains to be ascertained. Judging, however, from such observations as have yet been made in hot and deep mines, this wet-bulb temperature is not much above 80°."

My own experiments have so opened my eyes to the difference between the trained and the untrained man that I am inclined to wonder whether sufficient regard has here been paid to the extraordinary adaptability of man. The experimenter is not usually inured to the type and conditions of labour upon which his observations are being made, and his own system and reactions are, therefore, not necessarily the best to observe. The effects of adaptation may be expected to be more striking the nearer one approaches to the limits of what is practicable to the human machine. There is evidence that those who are used to hot damp air can do hard work at temperatures exceeding 80° Fahr. Mr. Eric Davies has recorded that, in a fairly good air-current in the Morro Velho Mine, Brazil, regular work is proceeding at a wet-bulb temperature of 84° or 85° Fahr. On occasions it is higher; in one instance, where hard labour such as loading and pushing trams was going on, it was 92-5°.\footnote{Trans. Inst. M. E., 1919-1920, vol. Iviii., pages 395-396.}

Again, Mr. J. S. Hayes has described in a recent paper how coal-mining is proceeding in Nigeria, with the air at the faces saturated at a temperature of 87° to 90° Fahr.\footnote{Ibid., page 244; see also \textit{Second Report of the Committee}, Trans. Inst. M. E., 1919-1920, vol. Iviii., page 323.}

It may be objected that in these instances native labour is employed. That is so; but the native is subject to the same physiological laws as ourselves. It is perhaps worth remarking that physical exertion at ordinary external temperatures induces a rise in body-temperature which is seemingly as much a normal concomitant of the exercise as the augmentation of blood-circulation and respiration. There is apparently nothing uncommon in the body-temperature rising to 102° Fahr. during exertion, and greater increases have been recorded. This increase in temperature is said to serve a useful purpose in facilitating the transfer of oxygen from the blood to the muscles, and in hot places it assists evaporation from the skin.

The great reduction in efficiency of the human machine which results from a high wet-bulb temperature is accountable, then, in the first place to the difficulty of keeping down the body-temperature. I wish to suggest a possible second cause, namely, that the hot damp air may impair the passage of oxygen from the air in the lungs to the blood. A recent experience lends colour to that view. A rescue-brigade were exercising with breathing-apparatus in a road in the Niddrie Colliery. A steam-pipe ran along the road; some steam was escaping, bringing the air to saturation-point at a temperature of 85° Fahr. After more than an hour's light work, a halt was called, and the Instructor (Mr. D. Davidson) advised the men to take out their mouthpieces and rest. They did so, but very soon slipped them back again, one by one. They preferred to breathe air from the apparatus—which by that time would also be saturated and of at least as high a temperature as the outer atmosphere—rather than fresh air from the road. The air of the apparatus would contain 70 or 80 per cent. of oxygen; it would, therefore, be more comfortable to inhale than normal saturated air at this high temperature if there were any difficulty in getting a proper oxygen-supply from the latter. This seems to be a point calling for investigation.

A fact which appeared during the research on mine-rescue apparatus was the high level of the expired-carbon-dioxide percentage of a miner performing a piece of work to which he was accustomed, as compared with that of a person to whom that task was strange. In some instances the carbon-dioxide percentage in the former case was nearly double that in the latter. The percentages of oxygen taken out of the air by the lungs of the two men in exchange for carbon dioxide were in similar ratio. In other words, the expert workman uses up the air he breathes more completely than the inexpert workman, and he breathes a correspondingly smaller volume per minute. There are exceptions to this rule, but they are few and far between. The adept has taught himself to carry out his duties with less respiratory exertion than the man who is inexperienced in that kind of labour, and therefore he is less apt to suffer from respiratory fatigue. This process of adaptation of the machine to its special duties is often most striking. As an instance in point, let us take the case of an underground official transferred from flat to steep workings. At first, and indeed for a considerable time, he finds the work of going his rounds specially hard, and that he is inferior to another man of similar physique who has been used to steep workings for several years. But in time, if the first man is not too old, his lungs and muscles become adapted to the new conditions: his expired-carbon-dioxide percentage becomes

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* Physiology of Muscular Exercise, by F. A. Bainbridge, 1919, page 18.
† See also Jules Amar, Comptes Rendus de l'Académie des Sciences, August 9th, 1920. This investigator found, in testing apprentices in engineering shops, that the respiratory economy increased with the degree of training attained.
adjusted to a new and higher level; he uses less air and uses it more thoroughly (compare the $A$ curves of the two mine officials, Subjects IV. and VII. ; the former works in fairly flat and the latter in steep seams).

The importance of physical fitness can scarcely be exaggerated in its bearing upon manual work. Other things being equal, the output of the fit man exceeds that of the unfit man, and he performs the day's labour with less fatigue. Physical fitness and dexterity often go together, but they should not be confused. The latter, which has already been discussed in some measure, is the result of training the brain and the muscles in relation to a special task; it can only be acquired by practice at that task. The training which leads to deftness teaches how to obtain the desired effect with a minimum of muscular effort, and therefore with a minimum waste of energy in the form of heat; it also leads to a strengthening of the group of muscles most adapted to perform the work. Fitness, on the other hand, is a much more general bodily attribute than this; it can be developed—and, indeed, is best developed—by all-round exercise, combined with a close attention to certain common-sense rules of living. When dexterity and fitness go hand in hand, we have the human machine in its most efficient state.*

The experiments carried out in Edinburgh on a large number of men from many walks of life have thrown considerable light on the subject of physical fitness. Fitness, indeed, has proved to be the efficiency of oxygenation of brain, heart, and muscles during exertion.

In the accompanying graphs (Figs. 1 to 7) the $A$ curves were determined when the subjects breathed normal air, the $B$ curves when they breathed almost pure oxygen. So far, reference has been to the former set only; we are now in a position to compare the two. Fig. 1 (Subject II.) is the record of a sedentary person of rather low fitness, and it will be observed that his $A$ and $B$ curves are far apart. Fig. 2 (Subject VIII.) relates to a sergeant-instructor in physical drill and a heavy-weight lifter; he was selected for the tests by the Superintendent, P. and B.T., Scottish Command, as representing the best physical material that the army can produce, and he was certainly the fittest man tested. The curves in his case are almost coincident, and their crests actually do coincide; it is only with over-loads (that is, those higher than the crest load) that the $B$ curve takes the upper place. Such a man as the latter derives no benefit from breathing highly-enriched air during exertion, while Subject II. gets a great deal of help therefrom. The degree of assistance from extra oxygen, indeed, is inversely as the fitness, and the curves enable physical fitness to be evaluated. This is done by drawing a horizontal $ab$ (Fig. 1), at the level of the carbon-dioxide percentage in the expired breath at rest, when the man breathes normal air, and then dividing the intercept $ac$ by the intercept $bd$ (in each of the other graphs, the carbon-dioxide percentage at rest is indicated by an arrow-head). By this method the fitness of the sedentary subject (Fig. 1) is 46 per cent., and that of Subject VIII. 100 per cent. So far as my observations went, the fitness of the healthy working miner is above 70 per cent., although I did not examine any underground worker over 45 years of age. The miners and officials who were tested were members of mine-rescue brigades. In one instance a member of a resident rescue-corps was tested; his fitness was found to be only 56 per cent. It appeared very likely that his fitness had deteriorated since he left the mines.

*It was agreed at the start that the intellectual aspect was to be kept out of the argument.
The method of measuring fitness here described was adopted for army purposes in 1918, and put into use at the Physical Test Station, Edinburgh. An analysis is given below of eighty-four persons tested at the station. They were drawn from all grades of society, and were mostly under 40 years of age.

<table>
<thead>
<tr>
<th>Proportion of men whose physical fitness was below</th>
<th>Per cent.</th>
<th>Per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>do. do. do. do. do. do. do. do. do. do. do. do.</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>do. do. do. do. do. do. do. do. do. do. do. do.</td>
<td>40 and 50</td>
<td>7</td>
</tr>
<tr>
<td>do. do. do. do. do. do. do. do. do. do. do. do.</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>do. do. do. do. do. do. do. do. do. do. do. do.</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>do. do. do. do. do. do. do. do. do. do. do. do.</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>do. do. do. do. do. do. do. do. do. do. do. do.</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>do. do. do. do. do. do. do. do. do. do. do. do.</td>
<td>90</td>
<td>100</td>
</tr>
</tbody>
</table>

Recent regulations require would-be mine-rescue men to undergo a physical as well as a medical examination before they can be accepted for training. The system of testing already described enables a physical examination to be made and fitness and stamina to be determined quantitatively.

The mechanical efficiency of the human machine has been investigated by several physiologists. Their results are in fair agreement with each other and with my own. The usual efficiency to be determined is the "gross" or overall efficiency, and the most convenient way of measuring the input of energy is from the oxygen-consumption. The consumption of a cubic foot of oxygen results in the development of a definite number of heat-units (which are easily expressed as units of work), depending upon the proportion of the oxygen going to form carbon dioxide and the proportion going to form water. The gross efficiency is ascertained by dividing the figure so obtained by the external work done while the oxygen was being consumed. To return to the analogy of the early part of this paper: the gross efficiency is equivalent to the brake-horsepower developed by the engine divided by the power put into the boiler-furnace and determined from the rate of burning of the coal and its calorific value.

Considerable difficulty is encountered in finding efficiency when the subject is dealing with an over-load, owing to the fact that, with such a degree of exertion, the oxygen required to support the exercise is not all taken in during the period of exertion; a great deal is supplied during the panting which ensues after the work ceases. The breathing does not quite settle down for several hours after a short spell of very hard labour. The state of affairs resembles that arising when the engine of the analogue is given an unusually heavy task and succeeds in doing it, for a short time, by drawing upon the steam stored in the steam-space of the boiler; after which effort it is compelled to stop or slow down until the boiler pressure and steam-reserve have been restored. If, in these circumstances, the horsepower transmitted by the crankshaft were divided by the horsepower generated as heat in the furnace while the engine was running, an erroneously high efficiency would be obtained. When the gross efficiency of the human machine is corrected, when necessary, by means of the excess of oxygen consumed during the post-work period, and efficiencies as ordinates are plotted against loads as abscissae, a domed-shaped curve again results. In other words, the gross efficiency increases with the load up to a maximum, and then falls again. The load at which the maximum efficiency is obtainable is the same as, or nearly the same as, the "crest load" as above defined. For most people the maximum efficiency, when breathing normal air, is in or near the region of 29 to 23 per cent. With highly-trained men, as was observed
by Benedict and Cathecart, the efficiency is increased, and these workers have recorded one of 33 per cent. The highest efficiency ascertained during my own experiments was 37 per cent.; it was the maximal value of a very remarkable athlete, G. P. Miller, of the Heart of Midlothian Football Club, when doing work on the ergometer at the rate of 6,500 foot-pounds per minute. Bearing in mind that the overall efficiency of a small non-condensing engine and boiler is usually less than 2 per cent., that that of a large high-class condensing engine and boiler is about 8 per cent., and that probably only with the Diesel oil-engine does the gross efficiency reach or occasionally exceed 20 per cent., it has to be allowed that the human machine stands on a high level among heat-engines. Unfortunately, the human engine cannot be worked long at its most efficient rate: fatigue reduces the efficiency. It is doubtful whether the gross efficiency of most heavy manual labour exceeds 10 per cent.

Some kinds of work are dealt with more efficiently than others: most healthy people are especially efficient in climbing stairs; rather less so on the ergometer, and still less so in climbing a mine incline, where the "going" is relatively rough and sometimes slippery. In general, the efficiency is a little higher when breathing oxygen than when breathing air; the fit man's efficiency exceeds that of the unfit man; and the efficiency of a person working at a job to which he is accustomed is greater than that of a man carrying out the same task when that task is strange to him.

The process of investigation of which the foregoing account gives an indication is capable of being much extended. Efficiency-studies on the human machine have been made with much care in the United States of America, and they have considerably influenced workshop arrangements and organization. Nor are they altogether neglected in this country, where, during the war, useful work was done, for example, in shell-filling factories on the relation between hours and output. This, and many other problems concerning the miner and his work, await the attack of the investigator, who is sometimes able to answer after a few months of experiment questions that have perplexed a generation.

In conclusion, I wish to acknowledge the very valuable assistance rendered in the course of the experiments alluded to by Miss Elizabeth Gilchrist, M.A., B.Sc., and Mr. D. Penman, B.Sc., Government research workers.

The President (Mr. Robert McLaren, M.P.): I cannot quite conceive how Dr. Haldane should object to the use of the term "human machine" as applicable to men and work, because it seems to me you could not have a better phrase. I think the author and his assistants deserve great credit for having tackled this interesting problem, because a great deal is being written in the newspapers about the capacity of certain classes for work. It is quite interesting to learn what the human machine is capable of doing, but it is another thing to get it to do that work.

The further discussion of the paper was adjourned.
nos.

The Military Physical Test Station, Edinburgh.

Professor Henry Briggs, D.Sc.
I. PURPOSE.

It became evident during the War that some men who are organically sound are nevertheless incapable of supporting heavy exertion; and among the older group that were called to the Colours in 1918 the proportion of such individuals was considerably more. The effect of forcing these men to carry out the duties falling to the lot of an "A" recruit was in many cases harmful to them and in extreme instances resulted in permanent disability and sometimes in death. The Army Medical Department therefore sought to obtain a method of physical examination, which would supplement the ordinary medical examination of a recruit, and which could be applied to men who proved to be unserviceable material in the hands of the drill sergeant, - a test which would, in fact, enable the malingerers to be distinguished from those who were truly incapable of sustained labour.

At that time, the writer was working on the same problem in its application to the members of mine rescue brigades, who, like the soldier, ought to be both medically sound and physically efficient.

The work was carried out under the auspices of the Scientific and Industrial Research Department, which also provided the material for the Test Station.
and he succeeded in developing a method of testing which quantitatively assesses the fitness and stamina of the subject. Acting on the advice of Col. Sir William Horrocks, K.C.M.G., the Army Council put the method into service for army purposes by setting up, in Edinburgh University, the Test Station of which this paper gives an account. Arrangements were being made in the Autumn of 1918 to establish a second Station under the Southern Command, but the signing of the Armistice in November brought the project to an end, and shortly after, the Edinburgh Station also ceased to function.

II. PRINCIPLES.

The principle upon which the method is based, and the experimental data bearing upon it have been fully described in the Journal of Physiology; it will therefore be sufficient to touch briefly upon the physiological aspect of the problem.

It was found that when a man breathing normal air is set to do physical work of gradually increasing amount, as, for example, upon a Martin's ergometer, the percentage of CO₂ in the exhaled air rises from the resting value (average, 3.31) to a maximum and then falls again. That is to say, if that percentage be plotted as ordinate against load in foot-pounds per minute as abscissa, a dome-shaped curve/

The evidence supports the view that oxygenation of the muscles doing the work is sufficient up to a load corresponding with the apex of the dome (the "crest-load", as it is conveniently called), but is inadequate for greater loads. Degrees of exertion which are less than the crest-load are termed "normal-loads" and can be supported for a considerable time, while those exceeding the crest-loads are "over-loads" and cannot be kept up for more than a brief period. Fatigue or illness reduced the "crest-load".

When the subject is caused to breathe air containing from 60 to 100 per cent of oxygen the effect with most people is to enable them to undertake hard physical work with greater ease and to carry it on longer without fatigue. In other words oxygenation is improved.

The result of breathing enriched air becomes evident when the graph connecting the degree of exertion and the expired CO₂ percentage is drawn, as at B, Fig. 1. It is then seen, with the average subject, that the CO₂-proportions are higher, especially at and beyond the crest-load, and that the crest-load itself is greater than when normal air was breathed. Oxygen-want, which is the main factor limiting the duration and intensity of physical exertion, is staved-off by breathing enriched air.
By experimenting on a large number of healthy men ranging in type from the athlete in perfect training to the ultra-sedentary person it was found that the higher the degree of fitness the less the A and B curves diverged, and, indeed, that when exceptionally fit men were tested the resulting graphs were similar to those of Fig. 2, where the curves for all practical purposes are coincident to the crest and only show divergence at the overloads. It was also discovered that if the same men were kept under observation for several months and were tested at different states of health, or at intervals during a course of physical training, the B curve would remain constant (within the limits of experimental error) but the A curve would vary in form and position according to the state of health or of training.

Fitness, which may be defined as the efficiency of oxygenation of brain, heart and muscles during exercise, is therefore inversely as the extent of divergence of the two curves, and can be evaluated.

By drawing upon the graph the horizontal line ac (Fig. 1) at the level of the expired-CO2-percentage at rest and then measuring the crest ordinates ab and cd, the fitness factor can be expressed as ab - cd. Thus, Fig. 1, which records the data for a sedentary man, gives his fitness as 46 p.c. while the curves of Fig. 2, which are those of an athletic sergeant-instructor in physical drill, show his fitness to have been 100 p.c.
If stamina be defined as the power of dealing with sustained exertion, it is clear that the wider the range of normal-load, i.e., the higher the crest-load, the higher must be the stamina of the subject. Hence the abscissal position of the crest-load becomes a measure of stamina.

Inasmuch as the "A" curve of a young man in good health rises during physical training until it eventually coincides with the "B" curve up to the crest, the latter curve may be regarded as expressing the subject's performance on air after he has been made quite fit; thus it was preferable to state the stamina as a function of the position of the crest of the "B" curve. The measure of stamina adopted at the Test Station was to take a "B" crest-load of 10,000 ft. lbs. per min. as indicating 100 p.c. stamina, a "B" crest-load of 5,000 ft. lbs. as 50 p.c. stamina, and so on. This method, though not free from objection, is simple and proved reliable.

III. APPARATUS and ROUTINE.

The Station was run by an officer and two N.C.O.s under the writer's superintendence. In the research which preceded the establishment of the Station, apparatus of rather greater complexity had to be employed, since the aim then was to evaluate oxygen consumption during work as well as CO₂-output and to study other questions such as the composition of alveolar air and the mechanical efficiency of/
of the subject; but at the Station the apparatus was cut down to the minimum and the routine was simplified and standardised for the sake of speed. The whole equipment, with the exception of thirty 100-ft. oxygen cylinders is shown in Fig. 2. The subject, it will be observed, was provided with mouthpiece and noseclip; he drew air or oxygen (as the case may be) through a dry meter and expired into a Douglas bag. The valves and connecting tubes were large, and their resistance was negligible even when the lung-ventilation was as high as 90 litres per minute. The meter, besides measuring the volume drawn in, served to indicate the rate of breathing; the officer in charge counted the movements of the pointer against a stop-watch. As the dial of the meter was not seen by the man he was unaware that any notice was being taken of his breathing - a matter of importance with "raw" subjects.

At the start, the empty Douglas bag was connected to the expiratory tube, A, the three-way tap being in the "off" position so that the products of expiration passed directly out into the air of the room. The subject, seated at rest on the saddle, breathed normal air. After he had become accustomed to his position, the three-way tap was turned "on" at the end of an expiration and the breath passed into the bag. After an interval of about two minutes the tap was again/
again turned at the end of an expiration. The bag was then placed on the table; kneaded to mix its contents; connected to the supply pipe of the Briggs analysis apparatus, B, and with the tap in the "on" position, squeezed to force a few litres through the burette. The sample so obtained in the burette was then analysed for CO₂. This procedure avoided the need for sample tubes or bottles. One of the N.C.Os. made the analysis during the time that the next sample was being obtained in the bag.

After filling the burette the bag was emptied by pressing it flat and was again connected to A. The subject was required to pedal at no load, i.e. with the belt off, for two minutes; the tap was turned on at the end of an expiration, and expired air allowed to accumulate in the bag for another two minutes of pedalling, when the sample was removed to the analysis apparatus. The belt was put in place; its cords were adjusted to give a difference of 3 lbs. between the balance readings, and the same sequence followed. Similar observations were made at balance-differences of 6, 9, 12 lbs, or even more, if the man could support such heavy exertion.

Pedalling was timed to a pendulum which swung 56 to the minute; at this rate, and with the gear of the cycle used, the work done was evaluated by multiplying the balance-difference by one-thousand.

Longer pauses were permitted between the heavier spells of work to allow/
allow the man to recover from the effect of one spell before attempting another. Care was taken that pedalling was kept up two minutes before opening the bag to the exhaled air; at the highest loads, however, e.g. 12,000 or 14,000 ft.lbs., this rule had to be relaxed as no-one in the writer's experience was able to bear them so long. The graphs at these extreme loads are therefore not so reliable as at lower ones.

After the above results had been obtained with the subject breathing normal air, an exactly similar series (excepting that the resting experiment was omitted) was taken with the man breathing oxygenated air from the reservoir bag which was kept, in a partially distended state, under the table at C, Fig. 9. Before the latter series was started he was required to sit still and breathe the enriched air for ten minutes.

The subject did not know that he was breathing oxygenated air. No loophole was allowed for any prejudice against so doing.

The oxygen was supplied to the reservoir bag, C, from a 100-ft. cylinder fitted with a reducing valve. On passing the reducing valve the gas flowed through an injector nozzle arranged so that the oxygen drew in, and diluted itself with, a certain proportion of normal air. The air entered through a pipe controlled by a tap which was set by trial (and then soldered in position) so that the mixture passing forward/
Fig. 9 is identical with Fig. 30 of the Second Report, Mine Rescue Apparatus Research, (Paper No 2).
forward to the reservoir bag was 40 p.c. air. Allowing for the impurity in cylinder oxygen, such a mixture contains about two-thirds oxygen. Besides the mixture being as good from the physiological point of view - even with the least fit subject - as pure oxygen, its use brought about a considerable saving in expense, oxygen being the chief item of cost of the Station.

The officer in charge entered all results as they were obtained and straightway plotted the graphs. A report, based upon his medical history and Test Station performance, was made out for each subject and forwarded to the C.O. of the Unit concerned. The report stated the physical capability of the man and his probable utility when trained. In the numerous instances where the tests showed him to be useless as a fighting unit, a recommendation was added in regard to the purpose (if any) to which he could be put.

A complete test, as described, took about 35 minutes. The time taken obviously precluded the use of the method for every recruit, and that was never the intention; the Station was set up to deal with special cases.

IV. RESULTS.

Specimen charts are reproduced in Figs. 1 to 8. The arrow-heads indicate the resting value of the CO₂ proportions. The "A" curves show the relation between load and expired-CO₂-percentage when breathing normal/
normal air and the "E" curves that when breathing oxygenated air.

When the Station was in operation men over 40 years of age were being conscripted, and many of these were examined. Only about 20 p.c. of them gave evidence of being worth training. The graphs indicated very clearly the influence of age, which reduces the "crest-loads" both on normal and on enriched air. In other words, anoxaemia (as might be expected) makes itself felt lower down the scale of exertion as age increases; stamina is reduced and a degree of exercise which would be a normal load to a younger man is an overload to an older one. The effect in question is shown by Figs. 3 and 4, of which the former is the record of a man of 44—a painter in civilian life—who was classed E.2 owing to kidney trouble, and the latter that of a well-developed and athletic cadet of 18. The report sent out in regard to the older man was: "Stamina: Very poor. Condition: Poor. Observations: Not worth training; no use as an infantryman. Recommendation: Suggest that he be set to his own trade." and that in regard to the cadet was: "Stamina: Excellent. Condition: Excellent. Observations: First-rate material; fit for anything. Probable increase of fitness from P.D., 10 per cent."

That a man of middle age, who is habituated in civilian life to physical labour, may sometimes preserve the physiological characteristics of youth is illustrated by Fig. 5, which gives the curves of a working miner.
miner, aged 42. Expressed on the system above described, his fitness was 79 p.c. and his stamina 30 p.c.

The physical deterioration brought about by wounds and hard active service is indicated by Fig. 7. In this instance the subject was a corporal, aged 32, who had joined the Army in 1914; he had suffered from trench fever and had been wounded three times. His medical category was A.1, but the tests showed that, though probably as fit as he was ever likely to be, his stamina had become so impaired that he was of no further use as an infantryman, and it was recommended that he should be re-boarded so that his category might be lowered.

The remaining charts, Figs. 6 and 8, are of special interest as representing the extremes of physical capacity. Both subjects were young men of "A" category; but while the former was a highly-intelligent instructor in physical drill, and a first-class footballer, runner, jumper and all-round athlete, the latter was deficient both physically and mentally.

A complete account of the numerous tests made upon the sergeant-instructor is given in the writer's paper in the Journal of Physiology, loc. cit. p. 302. When the curves of Fig. 6 were obtained he had a fitness of 70 p.c.; on the lightest loads he respired at the very low rate of 2.5 to 3 breaths per minute, and when dealing with a heavy load, like 12,000 ft.lbs., he only breathed 9 times per minute. As the/
the chart shows, his CO₂ level was very high and in consequence he used a small volume of air. For example, on a load of 6,000 ft.lbs., though the heavier man, his lung ventilation was less than half that of the sedentary subject of Fig. 1.

A good deal of trouble was taken with the degenerate subject of Fig. 8. He did not know how to pedal, and even after practice could not be induced to pedal in time with a pendulum. The record shows him to be useless in the ranks and not worth training; his stamina was far too low. His response to any form of mental stimulus was unusually tardy. An order, such as "Stop pedalling", would only be obeyed after the lapse of several seconds. Curiously enough, his respiratory centre appeared to operate after a similar lag, with the result that the volume of breathing did not increase at the normal rate upon starting a spell of work; anoxaemia supervened and made him stop the exertion at a load which to a normal healthy man would be easy.

Very few malingerers were met with. They were easily detected as they would allege a load was more than they could support before the curve had reached its crest.
The writer believed that it would be of use to the Oxygen Research Committee to present in a single paper an account of the results reached during the war, by experience and experiment, on the properties and modes of preparation of charcoal of high absorptive power. He also thought that it was advisable to set about the task of collecting this information as soon as possible, since the disappearance of the staff of Government Departments makes such a task a matter of increasing difficulty. Through the kindness of the Chemical Warfare Section, Directorate of Artillery, the various records and reports bearing on the subject have been placed at his disposal, and it is from these papers that the following account has been prepared. Since none of the papers in question have been published the Chemical Warfare Department requests that the information be regarded as confidential.

The Nature of the Absorption.

In the cases of certain easily reducible gases, e.g., phosgene, the charcoal acts catalytically in promoting chemical action; but the absorptio...
the absorption of more stable gases or vapours is of a different
nature and the phenomenon is variously referred to as occlusion, ad-
sorption, surface condensation and solid solution, according to the
physical explanation presumed. Certain facts of observation stand
clearly out:

(1) It has long been known that active charcoal absorbs a greater
volume of the more easily liquifiable gases, e.g. chlorine, than of the
"permanent" gases like nitrogen. Dewar showed that that rule holds
good when nearing the temperatures of liquefaction of the "permanent"
gases. One of the claims of his patent on the application of charcoal
in creating high vacua relates to the use of charcoal in separating
one gas from another; he takes advantage of the greater absorption of
oxygen in comparison with nitrogen as the temperature approaches
the boiling point of the former.

(2) The absorptive power of charcoal depends (a) Upon its
specific gravity; other things being equal, the higher the true
density of the substance (in contra-distinction to its apparent
density) the greater the volume it will absorb. (b) Upon its
porosity; with any given charcoal the more porous it is, up to a
limit, the more active it is; in other words low apparent density,
down to a limit, favours absorption. (c) Upon the nature of the
surface/
The surface of the charcoal, or, at any rate, of the surfaces within the pores.

(3) "Activation" i.e. the conversion of a relatively inactive charcoal into one of high absorptive power, is a process of slow oxidation during which porosity is increased and apparent density therefore diminished. The process is a failure in all cases where oxygen or oxidisers are excluded. Probably, also, the long-continued subjection of the walls of the pores, during that process, to bombardment with high-velocity incandescent molecules, improves the surfaces by ploughing or cratering.

(4) Properly stored active charcoal appears to retain its properties indefinitely.

Methods of Testing Absorptive Power.

In testing the activity of charcoal by the methods evolved by the Anti-Gas Department, use was naturally made of the gases used in warfare, e.g. phosgene, and chlorpicrin vapour. No heed was paid in this country to a charcoal's capacity for absorbing air or oxygen or hydrogen. It is stated that at Leverkusen, where the excellent German impregnated charcoal was made, the product was usually tested for its absorption of hydrogen or oxygen at the works, and:

* Subsequent work profoundly modified these views. See Paper No 6.
and that when the authorities in Berlin applied the phosgene test to charcoal of a variety or specific grade, different results were obtained. Though the results of tests with an easily condensable vapour like chlorpicrin are probably serviceable in placing a number of charcoals in their order of merit, the actual figures of comparative activities determined by the Anti-Gas

**Department, cannot be accepted for gas such as oxygen without further experiment.**

### Apparent Density and Comparative Activity of Charcoals.

*"box" test using chlorpicrin.*

<table>
<thead>
<tr>
<th>Charcoal Type</th>
<th>Apparent Density</th>
<th>Activity</th>
</tr>
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<tbody>
<tr>
<td>Birchwood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 hours burning</td>
<td>0.21</td>
<td>10</td>
</tr>
<tr>
<td>30 hours (respirator charcoal)</td>
<td>0.20</td>
<td>45</td>
</tr>
<tr>
<td>6 days burning</td>
<td>0.15</td>
<td>130</td>
</tr>
<tr>
<td>11 days burning</td>
<td>0.11</td>
<td>270</td>
</tr>
<tr>
<td>Fruit Stone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damson</td>
<td>0.42</td>
<td>80</td>
</tr>
<tr>
<td>Date Stone</td>
<td>0.36</td>
<td>82</td>
</tr>
<tr>
<td>Vegetable Ivory</td>
<td>0.40</td>
<td>82</td>
</tr>
<tr>
<td>Cocoanut</td>
<td>0.50</td>
<td>122</td>
</tr>
<tr>
<td>Charcoal briquetted with coal</td>
<td>0.38</td>
<td>74</td>
</tr>
<tr>
<td>American service mixture*</td>
<td>0.55</td>
<td>62</td>
</tr>
<tr>
<td>American Batchite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(steam treated anthracite)</td>
<td>0.70</td>
<td>52</td>
</tr>
<tr>
<td>French service charcoal</td>
<td>0.27</td>
<td>55</td>
</tr>
<tr>
<td>(impregnated)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>German (1916) ditto,</td>
<td>0.25</td>
<td>210</td>
</tr>
<tr>
<td>(impregnated)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Cocoanut anthracite and briquetted charcoals in varying proportions

### The Raw Materials Used:

The aim in this country has been to obtain a dense wood, of a structure favouring the production of a hard, porous, dustless charcoal. The same properties are desirable in charcoal for Dewar flasks.
flasks. Birch charcoal may consist of a carbon of specific gravity 2.2 (graphite 2.3), though, as the table shows in its most active condition its apparent density is as low as 0.11. The presence in this wood of open vessels interspersed among the cells explains the low apparent density and the friability of birch charcoal. Moreover, its habit of cleaving in flat chips militates against it packing closely in a narrow space.

Fruit-stone and cocoanut shells are made up entirely of thick-walled cells and yield active charcoals of high apparent density and relatively great hardness.

The most efficient charcoal tried by the Anti-Gas Department was prepared from palm-nut shell. It proved superior to cocoanut charcoal.

Date-stones were found to give a fairly good product, but beach husks were of little use. According to results obtained at Greenwich it is inadvisable to mix together different raw materials.

Messes. Sutcliffe and Speakman of Leigh, Lancs., have an extensive plant for the manufacture of a briquetted mixture of charcoal dust and powdered coal and they turn out an excellently graded product. In a recent letter to the writer they claim for the mixture a higher absorptive power than that of the British Anti-Gas charcoal.
charcoal. The table shows the relative activity of this briquetted material to be greater than that of the service charcoal, used during the War but now that the Anti-Gas Factory at Watford is engaged upon the production of charcoal, there is doubt as to the validity of the claim. The briquetted charcoal is apt to become dusty in time.

It is of interest that anthracite may be rendered active as a gas-absorbent. The American product known as Bachite is derived from high-grade Pennsylvanian Anthracite by the method described below. The writer is attempting to obtain some of this material for trial in vacuum vessels. Another American absorbent, called Carbonite, was made with considerable secrecy by the National Carbon Co., of Cleveland, Ohio, from lamp black by a process resembling that used in the production of arc-light carbons. Apparently the manufacture was expensive. Coalite was made in the U.S.A., from waste fine charcoal, pulverised to pass a 200-mesh sieve, which was mixed with soft pitch in the approximate proportions of 30% pitch to 70% charcoal. The mixture was activated by the aid of steam, and yielded a product nearly as good as nut-shell charcoal.

The Americans did a small amount of work on another charcoal substitute which, if it can be made sufficiently efficacious, possessed considerable attraction to the user of Dewar flasks in that it is non-inflammable. Equal volumes of 10% sodium silicate solution/
solution and 10% hydrochloric acid were mixed. The resulting
gelatinous precipitate of silica was allowed to set; washed free
of acid; dried and ground to size. It is stated that these silica-
gel granules displayed good activity when dry but rapidly deterior-
ated under the influence of moisture. The matter appears worthy of
further investigation.

Methods of Activation.

The manufacture of active charcoal involves two operations viz:
the preparation of "raw" charcoal and the conversion of the latter
into the active variety.

Before it was discovered how potent superheated steam is as an
agent in activation, the British product was prepared in gas retorts,
and the operations of carbonisation and activation were kept distinct
and performed in separate retorts. The tendency towards the end of
the War, however, was evidently in the direction of carrying out both
processes in one tube or retort.

Steam treatment has so far replaced the older method of
activation of subjecting the raw charcoal to a temperature of 900°
to 1,000°C. for 24 hours or longer that the original method used
by Dewar and applied at Greenwich may be dismissed in a few words.
At the latter place it consisted (a) of heating a charge of 4 - 5 cwt
of wood chips per retort for 6 hours with the "ascension pipe" open to allow the volatile products to escape readily; (b) of drawing and quenching the resulting raw charcoal and elevating it to bunkers preparatory to (c) charging it in batches of 140 lbs. into the activation retorts where it was heated for 24 hours before being withdrawn into bins and allowed to cool. As has already been stated, activation is a process of slow oxidation, and in this method air entered the retort during stage (c) through leaks in the doors and sides of the retort. If the heating continued too long SO₂ was found to diffuse through the walls of the retort with detrimental effect.

The introduction of steam treatment resulted in a marked saving of time and cost in comparison with the air treatment just described. Superheated steam may be introduced during carbonisation, it being made to enter through perforations in the fire-brick bed of the horizontal gas-retort in which that preliminary process is usually performed. Activation by steaming was carried on in one American plant in vertical nichrome tubes set in fire clay chambers and heated with gas by surface combustion to a temperature of 950°C. Each such tube was 7 ins. bore, and the steam at 300°C, delivered at the rate of 1 lb steam per lb of charcoal charged per hour, passed in through a perforated nichrome tube running up the 7 ins. tube. The charcoal/
charcoal was caused to pass through the latter tube at a slow, steady rate by a spider turn which removed a definite amount from the bottom of the tube at each revolution. A tube produced 25 lbs per hour of finished charcoal and the material took about 8 hours to pass through. In the preparation of Bashite (activated anthracite), the coking and subsequent activation were carried out in one retort.

Each retort (an inclined, oval gas retort) was fitted with a 3/4" steel steam pipe perforated with staggered holes, and running almost the length of the chamber. After charging with anthracite ground to 8 - 14 mesh a retort was heated by a coke fire to a temperature of 950°C, for a period of 8 - 12 hours; the material was then subjected to the action of steam (which was not superheated) for a time. The steaming caused the charge to cool down. As soon as the colour of the blue water-gas flame issuing from a hole in the charging door began to fade, indicating that the temperature had sunk too far, the steam was shut off until the temperature was restored, when the steam was again admitted. After 48 hours of this intermittent steaming the material was discharged into steel drums which were immediately sealed. This plant had an output of 20,000 lbs per day.

Some successful experimenting was done in America with a rotating furnace, charged with 6 - 14 mesh crude charcoal, and heated by the products of combustion from a powdered coal firing device.
device, the hot gases, together with superheated steam, being admitted into the kiln at the discharge end. The kiln was a cast iron cylinder 60 ft. long lined with firebrick; it was inclined at 1:12, and rotated at 20 revs. per hour.

Another suggestive experiment was made by the British. It was found that charcoal of high apparent density and considerable hardness resulted from the carbonisation of soft woods by sulphuric acid. A hundred percent improvement was brought about in this way on the apparent density of pine charcoal, with an equivalent increase of hardness. Birchwood subjected to this process yields a charcoal but little inferior in density and hardness to fruit stone charcoal. The result is due to the shrinkage of the wood tissue following upon energetic dehydration. The process was not carried beyond the experimental stage.

Impregnated Charcoals:

The enemy achieved remarkable success in preparing impregnated charcoal especially towards the end of the War. The method appears to have originated in Austria, and prior to 1916 the Germans imported their gas-mask charcoal from Aussig in that country. Subsequently they set up their own factory at Leverkusen. The table given above indicates to what a degree of perfection the process had developed by 1916. The method consisted of reducing any kind of wood—usually pine/
pine - to oven-sized pieces of about $\frac{1}{2}$ in. diameter, and then saturating it in HCl ($20 - 24^\circ$ Be strength) to which a small but indefinite amount of zinc chloride had been added. The soaking process, which took half-an-hour, was carried out on small quantities at a time in lead lined tanks. The acidified wood was then packed into a closed muffle, lined with porcelain tiles and connected by a stoneware pipe to an HCl recovery plant. Carbonisation took place slowly and very thoroughly, it being important to leave only a few inches of air space over the wood. The charge was kept at a cherry-red heat for 6 to 8 hours. The charcoal was then washed with hydrochloric acid in large lead lined tanks until the soluble ash had been reduced to a minimum. The acid was then washed out; the charcoal drained on a grid, transferred to a vacuum cupboard and dried at 70 - 80$^\circ$C. Finally it was sifted to remove dust. It is stated that the washing operations occupied two or three days. The finished charcoal contained 0.01% zinc.

Experiments had been made with sulphuric acid and with other chlorides in place of hydrochloric acid and zinc chloride but with unsatisfactory results.

The Allies, when experimenting on impregnated charcoals, obtained the following results:

"(a) When wood impregnated with zinc chloride solution is carbonised/
carbonised in a muffle to which there is access of air, for 4 hours at 900°C it is found that the charcoal obtained is far superior to that produced under similar conditions from untreated wood; the former has a considerably higher apparent density and a much firmer structure, while the yield is about twice that from the untreated material; the absorption capacity of the former is also very much greater.

"(b) If, however, the impregnated wood be carbonised in a furnace from which all air is excluded the absorptive capacity of the product before activation is the same as that of charcoal from untreated material, being practically negligible. The product responds to steam activation as readily as untreated material, but the absorptive capacities of the two charcoals after activation are approximately the same."

After April 1918 a more active charcoal was put into service by the Germans, and analyses showed it to contain both zinc and iron, the proportion of the former being much greater than indicated above. One sample gave 2.6% zinc and 1% iron, half the latter being in the ferric state.

The present writer reported to the Oxygen Committee in April, 1919, on certain German experiments conducted upon impregnated charcoal for Dewar flasks, and called attention to the special readiness with which ferruginous/
ferruginous charcoal ignites when drenched with liquid oxygen. It was not at that time clear how these charcoals came to hold so much zinc and iron, but the reason is now apparent. It may be recalled that Wöhler referred to charcoals having over 3.5% of iron.
Paper no. 7.

The Adsorption of Gas by Charcoal, Silica, and other Substances.

By Professor Henry Briggs, D.Sc.
THE ADSORPTION OF GAS by CHARCOAL, SILICA and other SUBSTANCES.

by Professor Henry Briggs, D.Sc.

This work is continued and is now being devoted to the adsorption of gases at liquid air temperatures.

I. INTRODUCTION.

The experimental work here described was carried out on behalf of the Oxygen Research Committee and the Mine Rescue Apparatus Research Committee of the Scientific and Industrial Research Department.

The main object of the experiments was to investigate the possibility of obtaining a non-inflammable substitute for the activated charcoal used in metal vacuum flasks intended for holding liquid air. As the work went on it was seen that its scope would need to be extended; it was realised that, by gaining a clearer indication as to the best direction to proceed, the inquiry would probably be assisted if an examination were made into some of the more theoretical aspects of the phenomenon of gas-adsorption.

The special problems presented by the metal vacuum vessel made it necessary to pay particular attention to adsorption at liquid air temperature, and as the principal cause of break-down of such a vessel is the slow inflow of air into the vacuous space it has been advisable to carry out most of the experimental work with nitrogen rather than with gases of higher boiling point. Nitrogen has the further advantage of being chemically indifferent to the substances tested.
This work is continuing and is now being devoted to the question of retentivity at low temperature.

II. PREPARATION of NON-INFLAMMABLE ADSORBENTS: their CAPACITY at LIQUID - AIR TEMPERATURE.

A large number of non-inflammable substances were prepared and were tested to ascertain their capacity for nitrogen at the temperature of boiling liquid air and at normal pressure. The method of preparation of many of these substances, together with their capacity under the stated conditions, are given below. The liquid air used had an average composition of 50 per cent oxygen and 50 per cent nitrogen; this mixture boils at \(-190^\circ C\). The materials, which were in the granular state, were tested in a uniform manner.

Immediately before being used, each sample was heated in a gas oven for several hours at a temperature (unless otherwise stated) of \(300^\circ C\). The sample was inserted, while hot, into a hot brass retort, containing nitrogen percolating from below.
of the kind shown in Fig. 2.

The retort consisted of two parts, namely, a hollow thimble, \(a\), holding exactly 2.5 ccm. and a perforated brass cap, \(b\), to which was brazed a fine-bore copper tube, \(c\). The cap screws into the thimble, and makes a tight joint against a copper washer. The retort was made of metal so that it might be used, without risk of melting or cracking, for both high and low temperatures.

When the sample had been put into the thimble and well shaken down, the cap was screwed on and a pressure test was applied to try the joint. The tube, \(d\), was then connected to a large gas-burette containing nitrogen standing over strong sulphuric acid. The retort being
being placed in a bath of cold water which furnished a definite initial temperature; the burette was read. The retort was then immersed in liquid air and allowed to stay there until no more gas was drawn in. During this operation the burette was lowered gradually into the sulphuric acid in order to keep the level of the acid inside the burette the same as that outside. After the state of saturation had been reached, the retort was withdrawn from the liquid air and allowed to regain its original temperature; the volume of gas expelled was measured as a check on the volume absorbed during cooling. A blank experiment made with an empty thimble gave the correction to be applied for contraction of the gas in the thimble and connecting pipe and for condensation upon the metal surfaces.

By far the most convenient receptacle for liquid air which I have used for experiments of the kind is the tauchoffas or dipping-flask made by the Berlin State Porcelain Factory. This is a U-shaped vacuum vessel, made of vitreous porcelain — for the most part unglazed — which was originally intended for service in connection with crystallization by action of chlorine, but unless great care be observed the use of liquid oxygen for explosives. In one convenient size, holding 6.5 lbs. of the liquid, the internal diameter is 10 cm., and the internal depth, 36 cm.; the porcelain flask is protected by an outer case of galvanized iron, there being a packing of corrugated paper/
paper between the two; a galvanised iron cover and a sling-handle for carrying are also provided. The weight when empty is 13.35 lbs. and the evaporation rate about 1.9 lbs. of liquid air per 24 hours.

In Table I, gas volumes are corrected to N.P.T., and they relate to the amount adsorbed between room temperature (average, 18°C) and -190°C. A sample was first tried with nitrogen, in the manner explained, and the result was stated as the number of cc. of that gas adsorbed per cc. of gross volume of the sample.

In certain cases a similar determination was made using dry hydrogen, and with the more important substances the results were also expressed in terms of the number of cc. of each gas taken in per gram of the adsorbent. For the sake of comparison, corresponding values are given for some of the activated charcoals. The silicas are set forth in chronological order, so that the remarks upon them may serve to indicate the stages by which high-capacity silica came to be evolved.

Dialysis was tried as the means of purifying the sols from crystallloids like sodium chloride, but unless great care be observed and the operation allowed to proceed very slowly, the sol is not cleansed sufficiently well. From a practical point of view the method of cleansing by successively washing and drying (see No 53) proved to be preferable.

- Gross volume includes the interstitial spaces, or voids, between the granules.
1. Activated by the steaming process.

2. Prepared by heating coconut shell in an electric pot furnace at 1,000°F for two hours.

3. -

4. -

5. Pine charcoal impregnated with zinc and iron; from German anti-gas drums, 1918.

6. -


8. One of the materials evolved in America towards the end of the war.

9. -

10. -

11. Well-weathered, spent oil-shale, from Straiton, Mid Lothian.

12. A proprietary substance being sold as a colloidal clay for absorptive purposes.

13. The material which comes from California, is a natural clay containing about 60% of silica and 25% alumina together with small quantities of iron, magnesia and calcium oxides. It possesses the extraordinary property of becoming, when water is added to it, a sticky paste which is being used in the U.S., in place of size and for other purposes. Part of the silica and alumina are in a soluble condition.
<table>
<thead>
<tr>
<th>Substance</th>
<th>Dry Nitrogen</th>
<th>Dry Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC. adsorbed</td>
<td>CC. adsorbed</td>
</tr>
<tr>
<td></td>
<td>CC. (gross</td>
<td>CC. (gross</td>
</tr>
<tr>
<td></td>
<td>per gram vol.)</td>
<td>per gram vol.)</td>
</tr>
<tr>
<td>Cocoanut charcoal, activated</td>
<td>129</td>
<td>62.3</td>
</tr>
<tr>
<td>Cocoanut charcoal, raw</td>
<td>66.3</td>
<td>-</td>
</tr>
<tr>
<td>Plumstone charcoal, activated</td>
<td>26.4</td>
<td>56.7</td>
</tr>
<tr>
<td>Birch charcoal, activated</td>
<td>66.3</td>
<td>-</td>
</tr>
<tr>
<td>German impregnated charcoal</td>
<td>91.1</td>
<td>63.8</td>
</tr>
<tr>
<td>Blood-charcoal</td>
<td>91.1</td>
<td>-</td>
</tr>
<tr>
<td>Messrs Sutcliffe Speakman's coal-charcoal preparation</td>
<td>91.1</td>
<td>96.7</td>
</tr>
<tr>
<td>Cleveland activated anthracite</td>
<td>5.6</td>
<td>2.7</td>
</tr>
<tr>
<td>Graphite, finely ground</td>
<td>5.6</td>
<td>-</td>
</tr>
</tbody>
</table>

**MINERAL SUBSTANCES:**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Meerschaum</td>
<td>34.4</td>
<td>-</td>
</tr>
<tr>
<td>Spent Oil Shale</td>
<td>2.95</td>
<td>-</td>
</tr>
<tr>
<td>Catalpo</td>
<td>2.2</td>
<td>-</td>
</tr>
<tr>
<td>Bentonite</td>
<td>12.4</td>
<td>-</td>
</tr>
</tbody>
</table>
14. Precipitated in a gelatinous form by adding ammonia to a solution of potash alum. No care was taken in this instance to clean the product of sulphate. The substance was dried as quickly as possible at a red heat.

15. Sample No 14, repeatedly washed until all trace of sulphate had gone.

16. Obtained by permitting oxidation to take place on an amalgamated aluminium sheet.

17. Prepared from sodium stannate and HCl; dried quickly. Doubtless a higher capacity would have resulted had the product been dialysed or otherwise thoroughly cleaned.

18. All the silicas, Nos 18 to 36 are prepared from water glass and hydrochloric acid. In this instance (No 18) the silica was precipitated in a gelatinous condition and rapidly dried, no attempt being made to remove the sodium chloride formed in the reaction.

19. In Nos 19 to 22 inclusive the sol was made by dissolving 60 grams of agar-agar in the mixture specified in No 25. Previous to the preparation of Nos 19 to 22 a considerable number of other adulterated silicas had been tried. In the case of No 19, the gel, after being dried in the vacuum oven at 100 °C, was dried further by being heated in a nickel crucible to 400 °C in an indifferent atmosphere. It was then given a succession of washes on a filter paper. Nos 20 and 21 were similarly treated except that they were dried at 600 °C and 800 °C respectively. These three results showed that it was preferable to dry the material at a low rather than a high temperature. Subsequently it was found (see Nos. 22 and 23) that drying at 300 °C yielded still better results, and this temperature was afterwards employed.
<table>
<thead>
<tr>
<th>Substance</th>
<th>Dry Nitrogen</th>
<th>Dry Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas. ad-sorbed per cc. (gross per gram vol.) of substance.</td>
<td>Gas. ad-sorbed per cc. (gross per gram vol.) of substance.</td>
</tr>
<tr>
<td>Alumina (unwashed)</td>
<td>8.9</td>
<td>-</td>
</tr>
<tr>
<td>Alumina (washed)</td>
<td>41.5</td>
<td>12.7</td>
</tr>
<tr>
<td>Sprouted Alumina</td>
<td>6.3</td>
<td>-</td>
</tr>
<tr>
<td>Colloidal Stannic Oxide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SnO₂</td>
<td>13.3</td>
<td>8.0</td>
</tr>
<tr>
<td>Colloidal Silicas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂ (1)</td>
<td>48.7</td>
<td>82.3</td>
</tr>
<tr>
<td>Agar-silica (a)</td>
<td>62.3</td>
<td>-</td>
</tr>
<tr>
<td>Agar-silica (b)</td>
<td>60.6</td>
<td>-</td>
</tr>
<tr>
<td>Agar-silica (c)</td>
<td>10.2</td>
<td>-</td>
</tr>
</tbody>
</table>
22. Prepared in the aforesaid manner but dried at 300°C.

23. An identical preparation to the last excepting that the material was more thoroughly washed.

24. Washed and dried in the same manner as No 22 excepting that Irish Moss was used instead of agar. A considerable number of silicas were made which were adulterated with Irish Moss at the gel stage.

25. In this and the following silicas (Nos 25 to 35), the manner of making the gel was a uniform one. Water glass was in the first place diluted so that 10 ccs. contained 1 gram of the salt; 2,200 ccs. of this solution and 200 ccs. of distilled water were added to 550 ccs. of hydrochloric acid. The mixture was immediately heated and stirred continuously by mechanical means until its concentration gave rise to gel formation. The gel was then allowed to cool. In this particular case the gel was broken up, washed until the washings gave no reaction with silver nitrate; it was then placed in a vacuum oven at 100°C for at least 12 hours, and was finally heated in a reducing atmosphere in a gas furnace at 300°C.

26. Made by exposing No 25, while hot, to thick smoke. The smoke was found to penetrate uniformly through the granules, which became jetty black in appearance. The product was afterwards heated in the gas furnace to dispel moisture and the volatile hydrocarbons.

27. The gel was treated as No 25, with the addition that it was again thoroughly washed on removal from the furnace and finally re-dried in the vacuum oven and then in the furnace. At this stage of the work it was realised that the presence of even a trace of sodium chloride was detrimental, and more and more attention was given to washing the product.

28. No 27 treated by smoking in the manner of No 26.

29. The gel was partially dried in the vacuum oven without washing; it was then more completely dried in the gas furnace. The substance was then washed by decantation till apparently free from chloride and dried in the gas furnace at 300°C.

30. The unwashed gel was partially dried by electric endosmosis, it being placed in a hollow, wooden cylinder having its lower end closed by a fine gauze over which filter paper was
TABLE I.

Desorption of Nitrogen and Hydrogen at Liquid Air Temperature and Atmospheric Pressure.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Dry Nitrogen (gaseous adsorbed per gram vol.)</th>
<th>Dry Hydrogen (gaseous adsorbed per gram vol.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agar-silica (4)</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>Agar-silica (a)</td>
<td>139</td>
<td>256</td>
</tr>
<tr>
<td>Moss-silica</td>
<td>116</td>
<td>-</td>
</tr>
<tr>
<td>SiO₂ (2)</td>
<td>131</td>
<td>164</td>
</tr>
<tr>
<td>SiO₂ (2) smoked</td>
<td>115</td>
<td>149</td>
</tr>
<tr>
<td>SiO₂ (3)</td>
<td>164</td>
<td>-</td>
</tr>
<tr>
<td>SiO₂ (3) smoked</td>
<td>151</td>
<td>-</td>
</tr>
<tr>
<td>SiO₂ (4)</td>
<td>194</td>
<td>-</td>
</tr>
<tr>
<td>SiO₂ (5)</td>
<td>164</td>
<td>197</td>
</tr>
</tbody>
</table>

**Note**: The table above shows the gaseous adsorbed per gram volume of substance for both nitrogen and hydrogen. The values are given in cubic centimeters (cc).
30. was spread. The gauze was connected to the negative terminal. Above the gel, and fitting the cylinder closely, was placed a weighted zinc disc positively connected. The appliance was allowed partly to de-water the gel by pressure only before the current was switched on. When the current passed through the gel a considerable additional quantity of water, with salt in solution, was discharged through the gauze. Above the gel, and fitting the cylinder loosely, was placed a weighted zinc disc positively connected. The appliance was allowed partly to de-water the gel by pressure only before the current was switched on. Then the current passed through the gel a considerable additional quantity of water, with salt in solution, was discharged through the gauze. The results obtained for substances dried in this manner, however, compared unfavourably with those in which the material had been dried in the gas oven; indeed, for all reasons the latter method of drying was found more suitable and was eventually the only one used. In this instance (No 30) the silica after the treatment specified was washed by decantation and finally dried in the furnace.

31. 0.5 gram of ferric chloride was added to the mixture specified in No 25 and the product treated exactly as in that case.

32. The sol was prepared as in No 31 and the cleansing and drying treatment were carried out as in No 30.

33. Prepared by drying the unwashed gel in the gas oven; plunging the product while hot into hot water; continuing to wash by decantation until the washings showed no trace of chloride; drying for the second time in the oven; again plunging into water while hot, and continuing this treatment until the material, when dropped in hot water, yielded no trace of chloride. As a final test some of the silica was boiled with weak silver nitrate solution to make sure that no opalescence was produced.

34. No 33 rammed down under pressure in the thimble, (a, Fig. 2) before testing, the object being to eliminate the greater part of useless interstitial space.

35. No 33 was heated by the blow-pipe for a short time circa 900°C, in order to dispel the last portion of the combined moisture.

36. Granules of translucent silica gel made for absorptive purposes by The Davison Chemical Supply Co., Baltimore, U. S. A. It was dried, as the makers recommend, at about 300°C before being tested.
A silica (No 33) can now be made - and the preparation can be indefinitely repeated with but small variations in the character of the product - whose capacity for nitrogen, at -190°C and atmospheric pressure, is, on the volumetric basis, greater than that of the best charcoal by 66 per cent.

III. PREFERENTIAL ADSORPTION.

Sir James Dewar was apparently the first (1905) to call attention to the fact that, if a table be drawn up showing the volumes of various gases adsorbed by charcoal under identical conditions, the order of the results is not that of the critical temperatures nor that of the liquefaction temperatures of the gases, but that the charcoal reveals a decided preference or affinity for certain gases. This phenomenon of preferential gas-adsorption has since been discussed by other writers.

It is revealed most clearly when the properties of two or more adsorbents are compared. Thus the striking partiality of charcoal and carbonaceous adsorbents for hydrogen stands out in high relief. When those substances are contrasted with the silicas or with alumina.

To effect such a comparison, the more important of the substances referred to in Table I have been re-tabulated below against numbers (first column) corresponding to those of the first table; information from other sources has been added, and, in the last column is stated the ratio/
ratio of the volume of hydrogen to that of nitrogen adsorbed at atmospheric pressure.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Temperature</th>
<th>Vol. of H2 adsorbed</th>
<th>Vol. of N2 adsorbed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CARBON GROUP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cocoanut charcoal (Hunter)</td>
<td>Ordinary</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Boxwood charcoal (de Saussure)</td>
<td>do</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>Cocoanut charcoal (Dewar)</td>
<td>-186°C</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>Cocoanut charcoal</td>
<td>-190°C</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Plumstone charcoal</td>
<td>do</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>Birch charcoal</td>
<td>do</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>German impregnated charcoal</td>
<td>do</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>Blood charcoal</td>
<td>do</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>Messrs. Sutcliffe-Speakman's coal-charcoal preparation</td>
<td>do</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>Activated Anthracite (Cleveland)</td>
<td>do</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Graphite, finely ground</td>
<td>do</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td><strong>ALUMINA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-195°C</td>
<td>do</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>SiO2 (8) packed</td>
<td>do</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>SiO2 (9)</td>
<td>do</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>SiO2 (8) ferruginous</td>
<td>do</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>SiO2 (7)</td>
<td>do</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>SiO2 (8) smoked</td>
<td>do</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>SiO2 (3) smoked</td>
<td>do</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Agar-silica (a)</td>
<td>do</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

It is observed that the volume of hydrogen adsorbed by the charcoal is greater than that of nitrogen.
It might have been expected that at temperatures like -185°C. or 
-190°C., which are only a few degrees above the boiling point of 
nitrogen but well above the critical temperature of hydrogen, the 
H/N ratio for charcoal would be less than at normal temperature; yet 
the reverse is true. Judging from the values of that ratio for 
cocoanut charcoal, at -185°C. and -190°C., its maximum occurs at a 
higher temperature than the former. In discussing a recent paper by 
\[(2)\]
N.K. Chaney, E. H. Sheldon stated that he had succeeded in making a 
charcoal which, at liquid air temperature, was more active upon 
hydrogen than upon nitrogen; the three examples he quoted give H/N 
ratios of 1.3, 1.2 and 2.1 respectively.

In the present state of knowledge it seems necessary to assume 
that the preference for hydrogen which charcoal reveals is due to 
the existence of a high specific attraction between the molecules of 
the two elements, carbon and hydrogen. That it does not result from 
the state of porosity of the adsorbent is indicated by the fact that 
the non-porous graphite (No. 9) was found to have, at -190°C., an 
H/N ratio much the same as that of the very porous blood charcoal (No. 6).

The stated results, however, seem to indicate that activation can 
intensify the preference, and that the presence of zinc and iron 
(as in No. 5) can reduce it. Silica has a low H/N ratio; but that 
proportion may be raised a little by partly filling the capillaries 
of/
of the silica with carbon deposited from smoke (Nos. 26 and 28), or by adulterating the silica at the col stage of preparation with seaweed col which carbonises in the subsequent stages. The addition of a small amount of iron, as in Nos. 31 and 32, also has a slight effect in the same direction. Alumina, though of much inferior capacity to colloidal silica for either nitrogen or hydrogen, has the higher H/N ratio.

Other instances of preferential adsorption are admissible: for example, carbon monoxide has a lower critical temperature than oxygen, yet, at ordinary temperatures, charcoal adsorbs more of the former than of the latter.

Inferior though silica may be as an adsorbent of one of the "permanent" gases at ordinary temperature, it is able to take in a considerable amount of water. Though individual results show wide discrepancies, on an average a well-cleansed silica is able to absorb more moisture from the air of a room than can cocoanut charcoal. The presence of a sodium chloride in the silica, though highly injurious to its capacity for, say, nitrogen at liquid air temperature, assists it in adsorbing moisture from the air; indeed with a certain proportion of salt the silica becomes about as deliquescent as calcium chloride.

It is clear that the composition of an adsorbent affects its powers/
powers profoundly. Much of the influence is physical in its nature, being concerned with the specific attraction between the solid and gaseous molecules, with the degree of porosity, and, (as I hope to show in a subsequent section), with the extent of polymerisation of the solid; at ordinary temperatures, however, chemical action may assist, and such appears to be the case when poison gases and vapours are absorbed by charcoal impregnated with zinc and iron, and possibly when silica saturated itself with moisture from the air. All the silicas finding places in the above tables, with the exception of No. 35, hold a proportion of combined water, and it is not unlikely that when they absorb moisture some of it also enters into loose combination. the pieces of about 20 per cent of solid matter and

The behaviour of an adsorbent at ordinary temperature is little or no guide to its behaviour at low temperature. For example, the capacity of charcoal for dry nitrogen is superior to that of silica at 15° C., but the reverse is true at -190° C.

IV. DETERMINATION of DENSITY and of the SOLID and GASVOUS VOLUMES of CHARCOAL and SILICA.

In a sample of granulated charcoal or silica the gross volume is made up of:

(a) The volume of the solid;

(b) The interstitial volume, i.e. that of the open spaces, or of a high-capacity absorbtion cannot be found by subtracting the volume voids/
voids, between the granules;

(c) The volume of the capillaries and polymeral interstices existing within the granules; This being spoken of below as the

internal gaseous volume.

It is important to ascertain the relation between these volumes, and especially between (a) and (c).

Other workers have published estimations of the relation between the internal gaseous volume and that of the adsorbent. The

first, apparently, was that of Mitscherlich, who avoided the problem of interstitial space by working with single pieces of charcoal.

Employing the immersion method, he found the charcoal used by him to consist, in the piece, of about 39 per cent of solid matter and

61 per cent of internal gaseous volume. W. D. Hartins and D.T. Ewing ascertained the "pore" volume to range between 53.4 per cent when

water, and 59.3 per cent when pentane was the liquid used.

(5) H. E. Miller and his associates estimated that in dried silica gel

(No 36, Table I), the internal gaseous volume was 41 per cent of that

of a granule.

In my measurements, which were carried out on granular material, interstitial space had of necessity to be ascertained. The problem

presented certain difficulties. For example, the interstitial space of a high-capacity adsorbent cannot be found by deducting the volume
of water displaced by a sample from the gross volume of the sample, since, when such a substance is put in water some of the adsorbed gas is expelled and the rapid development of bubbles on the granules causes an uplifting of the water-surface; after a while, when the bubbles have left the bath, the surface again sinks, and when quiescence is reached the water occupies the interstitial space plus an unknown part of the capillary passages.

The evaluation of the percentage of solid presented a still more formidable difficulty, which now falls to be considered: To obtain the solid volume, a sample, whether of charcoal or of silica, was placed in a dry graduated tube, well shaken down, and its gross volume observed. Its weight in vacuo was next found. The sample was then put into a bulb of combustion-glass, strongly heated and thoroughly evacuated by being connected, through a three-way tap, to a much larger bulb holding dry coconut charcoal and immersed in liquid air. After cooling the sample, the tap was turned and air-free water was allowed to enter the exhausted tube to a definite mark. The routine then followed that of the ordinary specific-

(4)

gravity-bottle method. As has been shown by Harkins and Ewing and by A. M. Williams, the specific gravity and therefore, the pro-

(3)

portional volume of the solid determined in this way is affected by

error.
error due to the high density of the layer of liquid actually in contact with the solid. It is clear that, under the agency of the error in question, a specific gravity so computed will be too high; that the more active the adsorbent the more serious will be the error involved, and also that the error will increase with the compressibility of the liquid employed. Williams has discussed the possible incidence of another factor militating against the accuracy of the results obtained by the immersion method, namely that of inadequate penetration, especially by large molecules such as those of chloroform, into the more minute intermolecular openings of the solid. An error of this character, however, would operate in the opposite sense to that due to compressibility and would tend to reduce the latter; further, when water is the liquid used it is difficult to imagine that there can be, in any part of a charcoal, an opening so small that the water molecule cannot enter, looking to the fact that these channels have been the vents through which larger hydrocarbon molecules made their escape during the carbonising process. In silica, again, where water was the only compound driven off in the gaseous condition during treatment, the passages through the solid must have served in the first place for the egress of steam, and therefore they are presumably accessible to the water molecule, though not necessarily to larger molecules.
Mankins and Ewing found that the density of a certain activated cocoanut charcoal, as ascertained by immersion, varied between 1.343 when water was used to 2.129 when pentane was employed. Other densities of cocoanut charcoal (ascertained by water-immersion) quoted by these workers are: 1.865, 1.835, 1.808; Tatoff gave 1.86, Baerwald 1.92 and Miss Homfray 1.86, - the last figure relating to a charcoal of comparatively inferior activation. Hulett (quoted by Chaney) got the value 1.84. I found the density of activated cocoanut charcoal (No 1, Table I) to be 1.86, and that of the "raw", but by no means inactive, material No 2 to be 1.74. For the reasons given, the former value is certainly higher than the true density. The true density could be ascertained, it may be suggested, by determining both the apparent density by water-immersion and the retentivity at normal temperature; then repeating the observations after activating the charcoal to a greater and greater extent. A graph of the data would enable the density at zero retentivity to be obtained by extrapolation. This method disregards the possibility of activation leading to the development of different allotropes - a kind of change for which, notwithstanding Chaney's interesting theories, there is no clear evidence.

Williams found the specific volume of blood charcoal, by immersion in chloroform at 25°C, to be 0.46; by an able theoretical analysis/
analysis based upon the experimental facts he then shows that, owing
to compression of the chloroform, this value was too low by 0.21.
That is to say, the true specific volume of the blood charcoal he
used was 0.67 cc. per gram, and the equivalent density was 1.42.
He had previously determined the density by water-immersion to be
1.96, - a figure which therefore turned out to be 32 per cent higher
than the true value.

The intensity of the forces of attraction at the surfaces of
such a silica as No 33, Table I, though greatly less than in the
case of charcoal, is appreciable, and, in consequence, the specific
gravity of the silica ascertained by the immersion method is also apt
to be too high. As will subsequently appear, it is possible with
silica to deactivate it completely; thus the apparent density in the
inactive and active states may easily be compared. The water
immersion method gave 2.30 as the specific gravity of No 33 and 2.00
as that ratio after deactivation. The difference would doubtless
have been greater but for the fact that, during deactivation, the
silica lost combined water.

The influence of the positive error affecting the ascertained
values of density or (what is the same thing) the negative error
affecting the volume of solid matter per cc. of gross volume of
the granules, is discussed in Section V.
In the case of cocoanut charcoal the most satisfactory way of measuring the proportion of interstitial space between the granules was to place a sample, well shaken down, in a wide tube of known volume, the inlet and outlet to the tube being by capillary stems into which the granules were too large to enter, and then to fill the interstices by admitting mercury. As the mercury did not wet the charcoal, the adsorbed gas remained quiescent. The volume of mercury entering between the granules was found by weighing. This method failed for the much smaller silica granules; the mercury would not enter all the interstices.

With only one of these substances was it found possible to get a reliable direct measurement of internal gaseous volume, namely with the deactivated variety of silica to which allusion has already been made, and this was done by means of the glass apparatus illustrated in Fig. 1. The apparatus consists of an open funnel, A; a bulb, B; a wide-bore stop-cook which allows of the bulb being closed off, and a capillary stem, D, of known volume per centimeter. A long, vertical glass tube was attached below D and connected by rubber pressure tubing to a levelling tube capable of vertical adjustment. The levelling tube held mercury, which, at the beginning of an experiment, was made to rise nearly to the top of the stem, E.

The bulb and the upper part of the capillary stem above the mercury were/
were filled with air-free water. A weighed sample of the deactivated silica was then dropped into the funnel, *A*, and drawn down into the bulb, where it settled round *C*, the crooked extension of the stem. The cock was closed and any water in *A* was poured out. The cock was now opened; the surface of the water adjusted to the mark, *B*; the cock closed, and the level of the mercury in the capillary stem was noted. After ejecting the air above *M* and the cock again closed, the levelling tube was lowered several feet to create a partial vacuum in the bulb and to cause the air in the sample to be emitted. After allowing some minutes to elapse, the pressure was restored and the air collected below the cock was expelled. The suction process was repeated, and these operations continued until no more gas could be drawn out. Finally, with the stop-cock open, the water surface was adjusted to the mark, *M*, and the position of the mercury in the stem observed. The difference, measured along the stem, between the first and last positions of the mercury in it, multiplied by the cross-section of the capillary tube, gave the internal gaseous volume of the sample. The measurement was reasonably reliable because deactivated silica has zero retentivity; therefore it parted with its gas readily under the influence of the relatively imperfect Tollicellian vacuum applied, and the water did not pass under compression when it entered the internal spaces vacated by the air.
Deactivated silica was found in this way to have an internal gaseous volume amounting to 6 per cent of the gross volume.

The figures of the following table do not take into account the compressibility of water and must merely be regarded as providing a first estimate, which, in the cases of the active substances, will need revision at a later stage. The solid volumes were found from the densities ascertained by the water-immersion method; the interstitial space of the charcoal was directly measured, and its contribution to these values, the internal gaseous volume and internal gaseous volume obtained by difference. The internal volume 81 per cent of the volume of the charcoal; the gaseous volume of the deactivated silica having been determined in the manner described, its interstitial space was got by difference; and, as the microscope showed the shape of the granules to be unaltered by deactivation, the same value (43 p. c.) was taken for active silica. Obviously, with the two active substances, the whole of the error affecting the evaluation of the solid volume 10°C was determined for the active charcoal (il in Table III) affects that of the internal gaseous volume, and as the former is too low the latter is too high.

\[
\text{Table 3:} \\
\text{Estimates of the proportional volume of solid matter, internal spaces and of voids, uncorrected for effect of compressibility of water.}
\]

<table>
<thead>
<tr>
<th>Substance</th>
<th>Proportional Volume of Solid Matter</th>
<th>Internal Spaces</th>
<th>Void Spaces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The table above shows the estimates for each substance.
Table 3.


<table>
<thead>
<tr>
<th>Substance</th>
<th>Volume of Internal Solid Matter</th>
<th>Volume of Gaseous Space per cent</th>
<th>Interstitial Space per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activated Coconut Charcoal, (No 1, Table 1)</td>
<td>29</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td>Activated Colloidal Silica, (No 33, Table 1)</td>
<td>27</td>
<td>30</td>
<td>43</td>
</tr>
<tr>
<td>Deactivated Silica</td>
<td>51</td>
<td>6</td>
<td>43</td>
</tr>
</tbody>
</table>

According to these values, the internal gaseous volume constitutes 53 per cent of the volume of a granule of the charcoal; the equivalent proportions for granules of active and deactivated silica are 52 and 10₂/₃ per cent respectively.

V. STATE OF ABSORBED GAS: FURTHER CONSIDERATION OF THE DENSITY OF THE SOLID MATTER.

The volume of dry nitrogen taken in at atmospheric pressure and 15°C was determined for dry coconut charcoal (No 1, Table 1) and dry silica (No 33). The sample was placed while hot in the brass retort, Fig. 2; well shaken down; the cap screwed tightly into place, and the joint tested for leakage. The tube, 2, of the retort was connected to a burette containing nitrogen standing over strong sulphuric acid. The retort having been placed in a water bath at 15°C, the burette was read. The retort was then put in a small electric/
electric pot furnace, the temperature was slowly raised above 300° C. and the volume expelled was measured. The retort was then allowed to cool again and the volume drawn in again observed. By alternately heating and cooling several times in this manner a reliable mean value was obtained. The mean was corrected by subtracting the volumetric difference due to simple expansion or contraction between the temperature-extremes, which was ascertained from a blank experiment. The results are given on the first line of Table 4; the second line is copied from Table 1.

**Table 4.**

<table>
<thead>
<tr>
<th>Gross Volume</th>
<th>Coconut Charcoal</th>
<th>Silica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adsorbed at 18° C.</td>
<td>5.5 ccs.</td>
<td>1.6 ccs. (N.T.P.)</td>
</tr>
<tr>
<td>Adsorbed between 18° and -190° C.</td>
<td>139</td>
<td>203</td>
</tr>
<tr>
<td>Total Adsorbed at -190° C.</td>
<td>154.5</td>
<td>204.6</td>
</tr>
</tbody>
</table>

Dewar, making use of Mitscherlich's value for the internal gaseous space (v. sup.) estimated the density of nitrogen adsorbed in charcoal at the boiling point of the gas to be 1.00, a value approximating to the density of solid nitrogen, 1.026. We may now attempt a similar estimation by the aid of the figures of Tables 3 & 4. Thus, in the case of silica, 204.6 ccs. of nitrogen at N.T.P. (Table 4) weigh 0.256 grams, and if, as Table 3 may lead one to infer, this/
this mass is condensed in a volume of 0\textsuperscript{0.30} cc., its average density, when adsorbed at -100\textdegree\textsuperscript{0}, must be 0.83. A similar determination for the charcoal gives 0.53 as the density of the adsorbed nitrogen at the same temperature. The density of liquid nitrogen, according to Baly and Donnan \cite{Baly_Donnan}, is 0.808 at -195\textdegree\textsuperscript{0} \cite{Baly_Donnan} (its boiling point at N.P.) and 0.735 at -190\textdegree\textsuperscript{0}.

Judging from the stated result for silica, the density of the adsorbed gas exceeds that of the liquid at the temperature in question, but it would appear that the reverse is true for charcoal. We know, however, that the specific attraction - i.e., the force subsisting between the solid and the gas molecules - is much greater with charcoal than with silica, and on that account would expect the nitrogen to be held in a denser condition in the charcoal. We also know from Desmar\'s experiments on the heat of adsorption \cite{Desmar} and from the observations and calculations of Williams and others that, in the stated circumstances, the gas must exist in charcoal in a state which is denser than the liquid. Clearly, then, the above estimate (0.53) of the specific gravity of the nitrogen adsorbed in charcoal is too low. The error is due to the fact that when Table 3 was drawn up, no account was taken of the compressibility of the water used in determining the density of the charcoal. In consequence (see Section IV), the estimate of internal gaseous volume was too high; hence/
hence the computed specific gravity of the adsorbed gas is too low.

For the same reason the value (0.83) for the density of the nitrogen adsorbed by silica will also be too low, though the error will, in this case, not be so large.

If 0.83 be assumed to be the correct value in the instance of cocoanut charcoal (and the evidence, as we have just seen, points to this being a low estimate) the internal gaseous volume amounts to only 20.4 per cent of the gross volume of the granules; the volume of the solid matter amounts to 39.6 per cent and the true density of the charcoal works out at 1.33. It may, therefore, be safely inferred that the true density of the cocoanut charcoal I used was under 1.33, instead of being 1.88 as appeared from the water-immersion determination.

So far attention has been principally focussed upon the case in which an adsorbent has been allowed to saturate itself at normal pressure and at a temperature only a few degrees above the boiling point of the gas adsorbed. Let us now consider the other extreme, namely the adsorption of a gas at low pressure or low partial pressure. In these circumstances the action differs markedly from that at high concentrations in that it follows Henry's Laws. The same holds true, very nearly, for the adsorption of gases like nitrogen, oxygen or hydrogen at ordinary temperature and moderate pressures.
pressures, and, as Miller's recent work shows, for SO\textsubscript{2} adsorbed by silica at temperatures of 100\(^\circ\)C. or more. At these low concentrations the attraction of the gas molecules for each other must be an influence altogether negligible in comparison with the attraction between the gas and the solid — a force which Williams calculates to be such that it is able to cause an aggregation of adsorbed molecules upon the surface of activated charcoal equivalent to that resulting from a pressure of about 10,000 atmospheres. Adsorption at low concentrations must depend, then, upon (a) the magnitude of this attraction (the specific attraction of the solid), and (b) the extent of solid surface exposed to the gas. It will not depend upon the internal gaseous volume since that volume is no criterion of the exposed surface.

As the concentration is increased the packing of the gas molecules upon the surfaces will also increase in density. Sooner or later a stage will be reached at which the gas molecules can only accumulate by adhering to others already anchored, and then the attraction of the molecules for each other will become a factor of importance. Eventually, as the temperature and pressure become such as to bring the outside gas near to liquefaction, the adsorption of gas molecules upon surfaces consisting of anchored gas molecules will proceed at an intensified rate; the finer, and finally the coarser, capillaries/
capillaries will fill up. The volume of gas (expressed at N.T.P.) which can be taken in at complete saturation will depend upon (a) the specific attraction of the solid as determining the firmness of anchorage of the initial layer and the degree of compression of that layer; (b) the thickness of the layer of compression; (c) the exposed surface as determining the extent of the layer of compression; (d) the compressibility of the liquefied gas; (e) the "internal gaseous volume" of the adsorbent, now filled with liquid, and (f) the relation between the densities of the gas and its liquid.

As the attachment of gas molecule to gas molecule at this latter stage cannot of itself produce a mass denser than the liquid at the particular temperature, and as the average density of the adsorbed gas has, in these circumstances, been shown to be greater than that of the liquid, it follows that the attraction of the solid for the gas molecule is greater than the attraction of the gas molecules for each other. It seems likely that we have, in this latter relation, one of the conditions essential to adsorption.

The differences between the characteristics of adsorption at low and high concentrations make it impossible to judge of the former from the volume of gas taken in during complete saturation; hence the figures of Table I bear no relation to the retentivity of the substances. Because it has a high capacity for nitrogen at normal pressure/
pressure and \(-190^\circ C\), a substance is not necessarily suitable for producing high vacua.

When the state of complete saturation is at hand each granule will be surrounded by a halo or envelope of condensed gas. The condensation effected by graphite, which has zero internal gaseous volume, must be entirely due to such an envelope, and, as Table 1 shows, this is by no means negligible with nitrogen at 5° above the boiling point of the gas. The argument used earlier in this section, to the effect that at complete saturation the internal gaseous volume is altogether occupied by liquid, should, strictly speaking, be modified to the extent needed to take this envelope into account. The correction implied would slightly reduce the computed average density of the adsorbed gas, though not sufficiently to affect the conclusions drawn.

VI. THE CONSTITUTION OF AN ADSORBENT.

When we turn from a consideration of the gas adsorbed to an analysis of the characteristics of the solid substance which acts both as condenser and as reservoir for that gas, we meet with phenomena, such as that of activation, whose effects can be studied by experiment but whose intrinsic nature, to a large degree, remains hidden. We are driven to devise hypotheses to explain these phenomena for, in searching for new adsorbents or for improved methods/
methods of preparation, even a crude hypothesis may turn out to be a useful practical guide.

It is unsatisfactory to speak of gas molecules being condensed upon the surface of the solid, since, if the gas is to be referred to the molar scale so must the solid; such a statement, indeed, compels the question, The surface of what? In the present state of our knowledge of the constitution of solids there appears to be no clear answer to that question. We are reasonably sure that, in solid substances such as carbon and silica, we are not dealing with the ultimate molecule but with elaborate polymers.

The manner of polymerisation has been made clear for certain crystals by Bragg and his co-workers; as a result of their labours it is no longer possible to hold the view that a solid is built up from ultimate molecules, each able to vibrate within its sphere of freedom, and each prevented by contact with its neighbours from moving out of position. Instead, it now seems more likely that, as with crystals,

I am indebted to Sir James Walker, for suggesting the expression 'ultimate molecule' to distinguish between $H_2O$ and $H_2O_n$, for example, or between the ultimate molecule $SiO_2$ and the polymeride $m(SiO_2)$. The expression removes much of the ambiguity of meaning attaching to the word 'molecule', which is not now always used in the original sense.
crystals, so with glasses, and many or even most solid forms, the
basis is the atom and not the ultimate molecule, and that structures
exist in which the atomic linkage has developed to the extent, though
without the regularity, which Bragg has made familiar in the case of
the crystal.

Apparently the only solid structures which are imprevisible to gas
are the crystal and the glass. As is well known, the former can hold
indefinitely gas "included" under pressure, while the latter, whether
common glass, vitreous porcelaln or fused silica, can hold a high
vacuum - and there is no better test of tightness - as long as the
character of the glass remains unchanged. That these two forms
possess so unusual a characteristic in common makes it probable that
they have analogous structures; that, in fact, in place of being a
molar aggregate (which would be pervious to gas), a piece of glass,
like a crystal, is a single atomic linkage, and as such is entirely
free from interstices on the solar scale. If this view be allowed, it
is clear that an adsorbent must be non-vitreous - an aspect of the
question which is further considered below.

It has already been seen, in Section III, that the chemical
character of the material affects its properties as a gas-adsorbent.
With any given material there are two other factors which have a
profound influence on adsorptive power, namely, (a) the degree of
adsorption
canalisation of the substance, i.e., its porosity on the microscopic or ultramicroscopic scale, and (b) the degree of porosity on the molecular scale.

The microscopic or ultramicroscopic canals, whose presence as an intricate network of connected passages is so striking a feature of a high-capacity adsorbent, important though their function is, do not alone determine adsorptive power. A high-capacity silica may be deactivated by prolonged heating, and though, in the deactivated state, one-fifth of the original internal gaseous volume remains, the amount of gas it can take in is virtually nil even at liquid air temperature. Evidently the capillaries are only of use when they traverse a medium in a suitable physical condition. Again, powdered graphite, which has no capillary passages, is able to adsorb 5.6 times its gross volume of nitrogen at -190°C.

The largest canals of charcoal can be seen under the microscope, and Saussure, who measured the size of the cells of charred wood, found them to be, on the average, $10^{-5}$ cms. in diameter, or about 13,000 times the diameter of a nitrogen or oxygen molecule. On the other hand, Lamb, Wilson and Chaney, from a study of the vapour pressure curves of adsorbed liquids, estimated the average diameter of the pores (assumed to be cylindrical) of activated charcoal - including the finest with the coarsest openings - to be about $5 \times 10^{-7}$ cms.
It may be inferred from these figures that the greater part of the internal gaseous space of an efficient adsorbent consists of passages which are not greatly larger than the gas molecule.

To draw an analogy: the coarser canals traversing the adsorbent may be compared with the bronchi of the lungs and the finer openings with the alveoli. Either kind of passage is useless without the other and their functions differ: the coarser canals convey and distribute the gas with a minimum of impediment, but (excepting in conditions approaching total saturation) they do not hold it; the gas is chiefly held on the surfaces of the polymers in openings of molar dimension.

It will be evident that a higher degree of porosity on the molar scale and a greater exposure of surface will occur when the polymers are small rather than large; and that (other conditions remaining constant) if we can disrupt the elaborate polymers which build up solid structures, the more active the material will become in adsorbing gas.

Reference has already been made to the fact that a high-capacity silica may be converted into a non-adsorptive substance by heating. The change is not due to the destruction of the capillaries, for 20 percent/
per cent of the original porosity remains after heating. Had adsorption been merely a matter of pore-space, one-fifth of the original capacity - or, at -190°C., about 40 vols. of nitrogen per gramme adsorbed with the charcoal used by him in storing high volume of silica - would have survived. Actually, the capacity fell almost to zero. The question arises: What happened to this silica secured in a shorter time by the method of supercooled glass, to cause deactivation? The microscope showed the particles to be unchanged in outward form, but here and there in the mass there was evidence of incipient fusion, which was revealed by the occasional presence of a few of the finest particles enclosed by a skin. At first it was thought that the formation of surface skins might explain the loss of adsorptive power, but when a sample was finely ground in an agate mortar there was no improvement; the change had affected the whole mass. The evidence favours the explanation that the heating, without destroying the coarser passages, had vitrified the silica, and blotted out the finest openings upon which adsorption so largely depends. In other words, the heating had converted a granule which was originally polymerised unit impermeable on the molar scale. 

VII. ACTIVATION.

It has long been known that if charcoal, and preferably a dense charcoal, be subjected to long-continued heating in the presence of a
small amount of oxygen its power of adsorption is greatly increased. This, the earliest process of activation, was developed by Dewar in connection with the charcoal used by him for obtaining high vacua. Recently it was discovered in this country that activation could be secured in a shorter time by the use of superheated steam, and this process, known as the steaming process, was considerably used towards the end of the war both in America and Great Britain. Lamb, Wilson (15) and Chaney state 350° to 450° to be the optimum temperature in the older, or air-activation process, though in this country it has been usual to carry it out at a considerably higher temperature. These writers advance the theory that activation mainly results from driving off the hydrocarbons which are residual in raw charcoal. No doubt the clearing of the charcoal of these substances is beneficial; but that it forms the chief object in activation is highly unlikely.

The theory falls under three objections: First, the small amount of volatile hydrocarbon which is left to be driven off in this manner is disproportionate to the result produced. Secondly, though the presence of oxygen would help in breaking up the hydrocarbons it would not be essential to their ejection; actually oxygen is found to be a necessity in the activation of charcoal. And thirdly, the residual hydrocarbons, as Chaney has shown, require a temperature exceeding/
exceeding 1000°C, before they are all dispersed, - a fact which appears difficult to square with the theory if 350°C to 450°C is the optimum in air-activation. Chaney's later hypothesis that active and inactive charcoal are different isotropes does not seem to be sufficiently supported by evidence.

The most probable explanation of the activation of charcoal would appear to be that, in common with other highly polymerised substances, its structure is apt to be simplified by heat. Heating to 1000°C without oxygen has no permanent effect. In other words, any cleavage or simplification of the polymers which may result from raising the temperature in a reducing atmosphere is followed by a re-aggregation on cooling. But if a little oxygen (either from air or from steam) be available when the polymers are split, some of the carbon is removed as CO₂; their cleavage is perpetuated; the porosity on the molar scale is increased, and with it, the surface accessible to gas.

Obviously, oxygen cannot serve in the case of silica the same useful purpose that it does for charcoal during activation, and to break down the silica polymer dependence has to be placed on water. The preparation of silica from the hydrogel by heating (see No 33, Table 1) involves the driving off of large proportions of water...
of water, different proportions being expelled as the
temperature is raised by given increments. As much, if not
most, of this water is chemically combined with the silica,
exsiccation will tend to break up the polymers. The last medium
of moisture is held with great tenacity and is only driven away
at a temperature exceeding 700° C. No 33, for example, was one
which had not been raised to this temperature and it therefore
held the residual moisture in combination.

As a means of activation, the expulsion of water from silica
is much less effectual than the heating and partial oxidation of
charcoal; the latter method gains by the fact that it can be
continued for several hours or days. The evidence supports the
view that the internal gaseous volume of a dried silica gel such
as No 33 consists of a higher proportion of capillaries on the
ultramicroscopic scale and a low proportion of openings on the
molar scale than that of activated coconut charcoal.

The influence of heat upon colloidal silica, apart from the
effect of dehydration just referred to, has certain points of
interest. A silica which has been imperfectly cleansed of sodium
chloride will, on heating, fuse into a glass negligible
adsorptive capacity. A silica chemically clean of chloride but
which was adulterated in the sol stage with carbonaceous matter
as, for example, with sea-weed sol, will, if heated above 750°C., yield considerable volumes of carbon dioxide, carbon monoxide and hydrogen through the interaction of the residual moisture and the carbonaceous matter. A chemically clean silica of very high capacity at low temperature, if heated by the blowpipe for a few minutes circa 900°C. so as to drive off most of the residual water, is not affected in its capacity for nitrogen at liquid air temperature; but if the same silica be kept in the electric furnace for five or six hours at 1000°C., its adsorptive power is destroyed, and if heated for a few hours at 750° to 900°C. it loses a considerable part of that power. We have here an example of an activated substance being deactivated by prolonged heating. The bearing of this result upon the problem of gas adsorption has already been discussed.

I desire to acknowledge the valuable help given by Messrs J. Mallinson, B.Sc., and W. Cooper, M.A., B.Sc., in obtaining the experimental data upon which this paper is based, and also the services of Mr J. J. Brodie in keeping the laboratory supplied with liquid air.
The method of determining the adsorptive capacity of a substance at liquid air temperature is described, and results are given of the capacity and manner of preparation or occurrence of 36 substances.

Charcoal and silica are compared, especially as relates to nitrogen and hydrogen, to illustrate preferential adsorption, and the influence of chemical composition on gas adsorption is discussed.

The effect of the compressibility of the initial layer, when the density of an adsorbent is determined by the immersion method, is considered. An evaluation is made of (a) the volume of solid matter, (b) that of the interstitial space between the granules and (c) that of the internal gaseous space for silica and coconut charcoal.

The density of the nitrogen adsorbed at $-190^\circ C.$ by silica and charcoal is calculated from experimental data. From these results it becomes possible roughly to estimate the error affecting the density of charcoal ascertained from water-immersion, and it is concluded that that method gave a result for the writer's coconut charcoal which was at least 0.55 too high. The conditions affecting adsorption at/
Section VI. The presence of capillaries is not sufficient to account for adsorption. A high capacity silica may be de-activated; and in the inactive state it remains porous. Graphite, which has no pores, adsorbs gas at -190°C. The evidence leads to the conclusion that deactivated silica is vitreous. It is argued that a vitreous solid, like a crystal, is a polymer, i.e., a complete atomic linkage. The importance of distinguishing between the coarser capillaries or canals and the finer interpolymermal openings of an adsorbent is emphasised.

Section VII. Activation is considered to be the effect of disrupting the solid polymers, and the means of accomplishing the partial depolymerisation of charcoal and silica are described.
REFERENCES.


An Experimental Analysis of the Losses by Evaporation of Liquid Air contained in Vacuum Flasks.

Professor Henry Briggs, D.Sc.
AN EXPERIMENTAL ANALYSIS OF THE LOSSES BY EVAPORATION OF LIQUID AIR CONTAINED IN VACUUM FLASKS.

by Professor Henry Briggs, D.Sc.

The experiments here described were made on behalf of the Oxygen Research Committee of the Scientific and Industrial Research Department, and the paper is given by permission of the Department. The fullest acknowledgement is due to Dr. J. A. Harker, F.R.S., and to his co-workers, Prof. G. W. Todd and Mr. H. S. Groom, who have, in a series of able memoirs presented to the Oxygen Committee, analysed the nature of the heat-transfer from the outer atmosphere to the interior of metal vacuum bottles. But for their memoirs it is doubtful if these experiments would have suggested themselves.

THE DEWAR VACUUM VESSEL.

The Dewar vacuum flask, which enables low boiling point liquids to be stored and transported, has been the principal means of rendering possible the great expansion now proceeding in the scientific and commercial uses of liquid air and liquid oxygen. These liquids are being increasingly employed as laboratory reagents, and are being put to service in mine rescue apparatus, for blasting, in aviation and therapeutics, and in evacuation plant.

Vacuum vessels are made in glass, silica ware, porcelain and metal; but for carrying and handling the liquids in bulk, only the last/
last kind is at present of much value. The glass vessels devised by Dewar in the course of his researches on liquefied gases and made by him in many forms, are too well known to need description.

Dewar described the metallic vacuum vessel in 1908, and not long after that date its manufacture was taken up in Germany, whence, before the war, all the flasks required at British mine rescue stations were obtained. During the latter part of the war these bottles became necessary for the Services and as a result of the exertions of makers and of the guidance of Government Research officers they are being successfully produced in this country.

The most convenient size of liquid air or liquid oxygen container or storage and transport flask, is designed to carry 50 lbs of the fluid. A metal container of this capacity and of proportions usual at the present time is shown in sectional elevation in Fig. 1.

It consists of inner and outer spheres, A and B, respectively 14 and 15 ins. in diameter, the inner one being suspended by a thin, narrow neck, C, of low-conductivity alloy which is soldered at its upper end into a metal plug, E. The space between the globes is evacuated through


through a lead pipe, which, when the operation is complete, is squeezed flat and sealed off by means of a flame; the pipe is finally protected (as is shown) by a metal cap containing bitumen or wax in which the end of the tube is embedded. The care needed in making these bottles will to some extent be realized from the fact that a high vacuum requires to be maintained through the agency of seven soldered joints. A dish-shaped metal spinning, is attached to the lower half of the inner globe and holds activated charcoal. This important addition is due to Dewar; without it, even a well-made and well-evacuated metal flask would not long hold a high vacuum.

In the container illustrated the charcoal is connected to the vacuum space by means of one or more openings in the dish, the openings being covered by fine gauze. At liquid-air temperature the charcoal's power of adsorption is very strong; it draws into and retains in its own capillaries and inter-molecular passages most of the residual gas in the vacuum space, and therefore automatically preserves the high degree of vacuum needed.

The inner surface of the outer globe and the outer surfaces of the inner globe and charcoal dish are high polished to reduce as far as possible the heat transferred across the vacuum space by radiation.

Most of the containers made in this country are constructed of copper — the metal which, with the sole exception of silver, has the lowest/
lowest emissivity. The German-built vessels now in this country are of brass, in the manufacture of which alloy, in its finest grade, the Germans are unrivalled. Dewar, before the war, built satisfactory vacuum flasks of nickel.

A first-class 50 lb. container loses, by tranquil evaporation, about 2.5 lbs of liquid air per day. The average loss of these vessels is probably about 3½ lbs.

CAUSES OF EVAPORATIVE LOSS:- Leaving out of account certain minor and negligible causes of heat-transfer, there may be said to be three ways by which heat from the outside atmosphere may reach liquid air stored in a vacuum flask. Stated in their order of importance for the case of a good flask, these are:

1. By radiation from the relatively warm outer vessel to the cold inner vessel;
2. By conduction across the vacuum space, and
3. By conduction down the neck of the flask.

When the vacuum is failing, conduction across the vacuum becomes responsible for a greater heat transfer than radiation.

Let \( \theta_1 \) be the absolute temperature of the hotter outer globe and \( \theta_2 \) that of the colder inner globe. Let us deal with the three processes of heat-transfer in the order given above:

1. Radiation: We are concerned in these experiments with heat passing/
passing from a relatively hot spherical surface whose temperature is caused to alter to a similar cold surface whose temperature remains constant, the latter being the boiling point of the liquid the vessel contains. Variation in the temperature of the hotter surface involves variation in the dominant wave-length of the radiation, and it is necessary to inquire whether this does not, in its turn, involve a change in emissivity.

The dominant wave-length in microns, \( \lambda_m \), and the absolute temperature of the hotter surface, \( T \), are connected by the expression

\[
\lambda_m / T = 2950.
\]

In the case of the three-litre gilding-metal flask (Fig. 2) whose evaporation rates were determined (see below) at external temperatures of 10\(^\circ\), 44\(^\circ\), 70\(^\circ\), and 100\(^\circ\)C., \( \lambda_m \) assumed the values 10.4, 9.4, 8.6, and 7.9 respectively. The gilding metal contained 95 per cent of copper, and although it will eventually be seen that its emissivity is considerably higher than that of the polished pure metal, it is justifiable to assume that the variation in emissivity, over the range of \( \lambda_m \) in question, will be similar to that of copper. The data available indicate that the emissivity of copper is very nearly constant between \( \lambda_m = 10.4 \mu \) and \( \lambda_m = 7.9 \mu \), and that if it be taken as 0.016 it will be correct over the whole range to the third place of decimals. The emissivity of gilding metal has accordingly been regarded as constant for the temperatures used.
used in the tests described below.

The first of the analyses here attempted is based upon figures given by Dewar for a glass flask in which the inner vessel was "silvered" with mercury, the outer one being untreated. The evaporation loss of the flask was ascertained over a temperature-range (of $\lambda$) extending between $158^\circ$ abs. and $338^\circ$ abs. Information does not appear to be available regarding the change of emissivity of glass and mercury surfaces over such a wide range of $\lambda$, as it here involved and the emissivity has again been assumed to be constant between the stated extremes of temperature. Owing to the uncertainty resulting from the incompleteness of the physical data, the results obtained for the glass flask must be regarded only as rough approximations. When emissivity is constant, the heat radiation may be expressed as

$$L_R = a \left( \frac{1}{r_1^4} - \frac{1}{r_2^4} \right),$$

in which $a$ is a coefficient depending upon the emissivity of the surfaces and upon their dimensions. The unit may be calories per second, or, as is here more convenient, grams of liquid air evaporated per hour.

(2) Conduction across the Vacuum Space: With the highly refined vacua which we are concerned, the mean free path of the gas molecule is greater than the distance (about 1 cm) between the hot and cold surfaces; hence, if conductivity had been independent of temperature/
temperature, the heat carried by conduction across the vacuum would be proportional to \((T_1 - T_2)\). In a gas, however, the conductivity varies as the square root of the abs. temperature, and, as the mean temperature across the vacuum space is \(0.5(T_1 + T_2)\), the expression representing the evaporation loss due to this cause, is, in grams of liquid air, evaporated per hour.

\[ L = \frac{t}{\sqrt{\frac{T_1 - T_2}{T_1 + T_2}}} \quad \ldots \ldotted
though proportionately less, i.e., in grams per hour, actually more than in a small vessel. It therefore, follows that as the size of the flask is increased the neck may be shortened, or, alternately, made stouter, without the evaporation rate due to neck conduction being affected. Heat-transfer along the neck is studied experimentally in a later part of the paper.

In the cases examined, the temperature of the gas issuing from the mouths of metal vacuum flasks containing liquid air lay between \(-4^\circ\)C and \(-30^\circ\)C. As the inner globe is made of so good a conductor as copper, gilding metal or brass, its temperature may be regarded as uniform at all points of the sphere, that temperature being the boiling point of the liquid. It is therefore apparent that the heat transferred to the inner globe by radiation and conduction across the vacuum space is all absorbed in giving latent heat to the gas boiled off, and that the neck alone is responsible for heating the evaporated gas from the boiling temperature to that at which it discharges into the outer air.

**EVALUATION of the EFFECTS of RADIATION AND CONDUCTION for a**

**GLASS FLASK.**

The writer's method of analysing the tranquil evaporation-rate of a vessel holding liquid air or oxygen so as to apportion the amount of loss due to the three several causes set forth above, is indicated/
indicated by the present example, which consists of a simplification of the general problem in that the transference of heat down the glass neck, and in opposition to the upward flow of cold gaseous oxygen, must have been altogether negligible.

Dewar filled a glass vacuum flask with liquid oxygen (boiling point, -183°C) and measured its evaporation rate when the flask was immersed in liquids maintained at different temperatures, with the results stated in Table I. At that time (1883) the vacuum was obtained by washing out the space between the inner and outer vessels with mercury vapour, and then exhausting. Some condensation of the residual vapour took place when liquid oxygen was introduced, causing the formation of a mercury mirror on the surface of the inner vessel.

**Table I.**

<table>
<thead>
<tr>
<th>Temperature of Outer Vessel</th>
<th>Absolute Temperature of Outer Vessel</th>
<th>Absolute Temperature of Inner Vessel</th>
<th>Evaporation Losses per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>-115°C</td>
<td>158°</td>
<td>91°</td>
<td>30</td>
</tr>
<tr>
<td>-78</td>
<td>182°</td>
<td>91°</td>
<td>120</td>
</tr>
<tr>
<td>16</td>
<td>272°</td>
<td>91°</td>
<td>370</td>
</tr>
<tr>
<td>65</td>
<td>332°</td>
<td>91°</td>
<td>600</td>
</tr>
</tbody>
</table>

Neck-loss being inconsiderable, the total evaporation loss, L, is the sum of the losses due to radiation and conduction across the vacuum.

*Sir James Dewar, "Liquid Atmospheric Air", ibid XIV, p. 1.*
Fig. 2

SCALE

A

B

C

D

E

F

G

INS.
vaccum; or, from equations (1) and (2):

$$L = a \left( \frac{1}{\beta_2^4 - \beta_1^4} \right) + b \left( \frac{1}{\beta_2^4 - \beta_1^4} \right) \sqrt{\beta_1 + \beta_2} \ldots \ldots (3)$$

The values of the table are in reasonable agreement with the equation:

$$L = 3.01 \left( \frac{1}{\beta_2^4 - \beta_1^4} \right) 10^8 + 0.041 \left( \frac{1}{\beta_2^4 - \beta_1^4} \right) \sqrt{\beta_1 + \beta_2} \ldots \ldots (4)$$

The first term on the right-hand side of the equation expresses the loss due to radiation and the second that due to conduction. At 15°C radiation was responsible for the evaporation of 236 ccs. and conduction across the vacuum for 138 ccs. of gas per minute. Had the flask held liquid hydrogen instead of liquid oxygen the losses at that external temperature would have been: 238 ccs. and 187 ccs. per minute respectively.

**ESTIMATION of the THREE CAUSES of EVAPORATION LOSS for a SMALL METAL FLASK.**

The vessel is illustrated in Fig. 2. It is a vaporiser flask, i.e., one whose function it is, by the aid of certain fittings, to evaporate liquid air at set rates. The fittings are not shown; they were not attached during these tests. The capacity of the flask is 3 litres (about 7 lbs); it is made of gilding-metal (95 percent copper; 5 per cent. tin), and the inner neck $C_2$ is of cupronickel, an alloy having one-seventh the conductivity of copper. The charcoal (plumatone) is in this instance held in a copper tube, $E$, passing through/
through the inner globe, the ends of the tube being covered with

gauzes. The spheres are respectively 8 3/16 ins. and 7 1/8 ins. in
diameter, and their surfaces are 230 and 177 sq. ins. or 1419 and
1152 sq. cms. in area. The neck is unusually short and wide in

comparison to the size of the bottle, it being 3 1/2 ins. long, of which

only 9 3/8 ins. (6 cms.) are surrounded by vacuum. The bore of the

neck is 5 5/8 in. and the metal 0.024 in. in thickness; there is 0.047
sq. in. or 0.303 sq. cm. of metal in a cross-section of the tube.

Before any of the following observations were made, the flask

held liquid air for twelve hours. It was never allowed to boil
empty during the fortnight over which the test extended. The same

weight of liquid air (5 lbs.) was put in, and about 2 lbs. of air were

allowed to evaporate on each "run". The exact losses were ascertained

by weighing. The lowest of the external temperatures recorded below

was obtained by standing the flask in a cellar, and the others by

immersing it, up to the base of the neck-screw, in a water-bath kept

at constant temperature. The average composition of the liquid air

was 50 per cent oxygen, 50 per cent nitrogen, and was found from

samples of the liquid drawn from the flask at the beginning and end

of a "run". This mixture boils at -191 °C. The ascertained losses

at different external temperatures are given in Table II.

Temperature measurements of the air passing up the neck were

made.
made during the first few tests in order to find out if neck-loss was serious. They showed that, (a) with the short neck in question, this source of loss could not be neglected, and (b) the neck-loss was proportionately less important as the outside temperature rose.

### TABLE II.

Metal Flask: Evaporation Losses at Different External Temperatures.

<table>
<thead>
<tr>
<th>Period of Test hours</th>
<th>Temperature of outer Globe</th>
<th>Absolute Temperature of outer Globe</th>
<th>Absolute Temperature of inner Globe</th>
<th>Evaporation Loss, grams per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 21</td>
<td>10°C</td>
<td>283°</td>
<td>82</td>
<td>42.5</td>
</tr>
<tr>
<td>(b) 16 $\frac{1}{2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c) 14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d) 11 $\frac{1}{2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) 13 $\frac{1}{2}$</td>
<td>44°C</td>
<td>317</td>
<td>82</td>
<td>61.3</td>
</tr>
<tr>
<td>(b) 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) 13 $\frac{1}{2}$</td>
<td>70°C</td>
<td>343</td>
<td>82</td>
<td>72.0</td>
</tr>
<tr>
<td>(b) 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) 9 $\frac{1}{2}$</td>
<td>100°C</td>
<td>373</td>
<td>82</td>
<td>97.6</td>
</tr>
<tr>
<td>(b) 9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To enable neck-loss to be evaluated, independently of the other modes of heat-transfer, an inner tube of cupronickel of the same length as the neck was slipped inside the latter, and the evaporation rates were again determined at the selected temperatures. By inserting this extra tube, the sectional area was increased from 0.303 sq. cms. to 0.356 sq. cms. of metal. The enhanced rates of evaporation are described in Grundlagen zum Bau von Transportgefäßen für verflüssigte Gase, by F. Barweitz, G. Rein and B. Kurr, Annalen der Physik, Vol. 61 (1920), p. 113.

evaporation resulting therefrom are set forth in Table III.

### Table III

<table>
<thead>
<tr>
<th>Period of Test, hours</th>
<th>Absolute Temperature of Outer Globe,°</th>
<th>Absolute Temperature of Inner Globe,°</th>
<th>Evaporation Loss, grams per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>203</td>
<td>22</td>
<td>8.5</td>
</tr>
<tr>
<td>13</td>
<td>317</td>
<td>22</td>
<td>89.4</td>
</tr>
<tr>
<td>61</td>
<td>345</td>
<td>22</td>
<td>99.7</td>
</tr>
<tr>
<td>7</td>
<td>372</td>
<td>22</td>
<td>124.1</td>
</tr>
</tbody>
</table>

It will be observed that when the outside temperature was 10°C (283° abs.) the extra tube added 20 grams per hour to the rate of evaporation. By simple proportion, the neck-loss at this temperature when the additional tube was absent was 11 grams per hour. The equivalent losses at the other stated temperatures (Table IV) were obtained in the same manner.

To make sure that the flask was not deteriorating under the treatment it was receiving, frequent check determinations were made of the normal evaporation rate at 10°C. There was no sign of deterioration.

### Table IV

<table>
<thead>
<tr>
<th>Absolute Temperature Outer Globe,°</th>
<th>Increase of evaporation due to insertion of extra tube, 0.553 sq. cm. section; grams per hour</th>
<th>Evaporation per sq. cm. of neck section; grams per hour</th>
<th>Actual Neck-Loss, grams per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>283 (29°C)</td>
<td>26.0</td>
<td>36.2</td>
<td>11.0</td>
</tr>
<tr>
<td>263 (15°C)</td>
<td>26.1</td>
<td>50.2</td>
<td>11.3</td>
</tr>
<tr>
<td>317</td>
<td>27.7</td>
<td>50.1</td>
<td>15.4</td>
</tr>
<tr>
<td>343</td>
<td>24.5</td>
<td>43.2</td>
<td>15.3</td>
</tr>
<tr>
<td>372</td>
<td>26.3</td>
<td>43.2</td>
<td>14.3</td>
</tr>
</tbody>
</table>

*Inte*.
The last table shows that as \( \beta \) increased, the neck-loss rose to
a maximum and then fell. The fall was due to the fact that the
stream of cold-air passing up the neck increased at a more rapid rate
than did the passage of heat down the metal of the neck.

By subtracting the ascertainment neck-losses (Table IV) from the
total losses (Table II) the rates of evaporation \( (L) \) due to radiation
plus conduction across the vacuum were obtained (Table V):

**TABLE V.**

<table>
<thead>
<tr>
<th>Metal Flask: Losses due to Conduction plus Radiation Across the Vacuum: Neck-losses eliminated.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Temperature</td>
</tr>
<tr>
<td>Outer Globe: ( \beta_i )</td>
</tr>
<tr>
<td>263</td>
</tr>
<tr>
<td>317</td>
</tr>
<tr>
<td>343</td>
</tr>
<tr>
<td>373</td>
</tr>
</tbody>
</table>

With these values equation (3) takes the form:

\[
L = 3.228 \left( \beta_i - \beta_f \right) \sqrt{g} + 0.00284 \left( \beta_i - \beta_f \right) \sqrt{a + \beta_c} \ldots (5)
\]

Since, as before, the first term of the right-hand side of this
equation determines radiation and the second term determines conduction
the complete analysis of the loss by evaporation is now possible. It
is given in Table VI, the values for neck-conduction being copied from
Table IV. The degree of agreement between the results derived from
equation (5) and those obtained by experiment may be gathered by
comparing the last columns of Tables II and VI.

**TABLE VI.**
(15).

**TABLE VI.**

Metal Flask: Losses due to Conduction, Radiation and Neck, Severally Stated.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Conduction, Outer Globe, across Vacuum 10 CMS per hour</th>
<th>Radiation, grams per hour</th>
<th>Neck conduction, grams per hour</th>
<th>Total loss, grams per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10.9</td>
<td>20.6</td>
<td>11.0</td>
<td>42.5</td>
</tr>
<tr>
<td>15</td>
<td>11.3</td>
<td>23.1</td>
<td>11.9</td>
<td>45.3</td>
</tr>
<tr>
<td>44</td>
<td>15.3</td>
<td>32.5</td>
<td>15.4</td>
<td>63.2</td>
</tr>
<tr>
<td>70</td>
<td>15.3</td>
<td>44.5</td>
<td>15.2</td>
<td>75.0</td>
</tr>
<tr>
<td>100</td>
<td>17.6</td>
<td>62.4</td>
<td>14.6</td>
<td>94.6</td>
</tr>
</tbody>
</table>

The radiation loss at ordinary temperatures is thus, in this flask, about twice that due to conduction of heat across the vacuum space.

PRESSURE in the VACUUM SPACE of the 3-litre FLASK and EMISSIVITY of the METAL SURFACES.

The results stated in Table VI allow the emissivity of the reflecting surfaces of the flask and the degree of tenuity of the vacuum to be obtained.

Before emissivity can be calculated it is necessary to inquire into the manner of heat-exchange, by radiation, of two reflecting surfaces facing each other. The following demonstration is due to J. A. Harker:

Let the emissivity of either of the two similar surfaces be \( E \).

Suppose \( E \) units of heat to be emitted by the hotter surface; of these \( E^2 \) will be absorbed and \( E(1 - E) \) will be reflected by the second or cooler.
cooler surface. The first surface will then reflect \(E(1 - E)^2\) units, of which the second surface will absorb \(E^2(1 - E)^2\). Proceeding thus, it appears that when the hotter surface emits \(E\) units the colder surface gains an amount which is the sum of an infinite G.P. whose first term is \(E^2\) and whose common ratio is \((1 - E)^2\), and that summation is \(\frac{E}{2 - E}\). Applying this result to Stefan's Law; taking the constant of that law as \(1.395 \times 10^{-12}\) (calorie units); taking the latent heat of a half-and-half mixture of liquid nitrogen and liquid oxygen as 50.2 cals. per gm.; and making use of the dimensions of the flask, the emissivity of the gilding metal surfaces was found to be 0.050. That for pure copper polished to the highest degree is 0.016. The fact that the makers of the flask have only succeeded in getting an emissivity amounting to thrice that of copper is important. In studying to reduce the tranquil evaporation rate in these particular flasks it is evidently upon the radiation loss that most attention should be focussed. A small increase upon the value for the emissivity of copper might have been expected owing to the gilding metal containing tin, and a further slight increase is no doubt due to the smear of solder running equatorially round the inner sphere; but the main reason for the enhanced radiation is probably that water vapour condensed on the inner sphere and spoiled the surface. It is a most difficult matter, with the method of evacuation used at/
at present for soft-soldered metal flasks, to rid the charcoal and vacuum space entirely of water vapour.

With pressures as low as those in the vacuum spaces of liquid-air bottles, the heat-transfer by conduction across such a space is proportional to the difference of temperature \((\theta_1 - \theta_2)\), to the pressure, \(p\), and to the area of the surface, \(A\), and is independent of the distance.

That is to say:

\[
\text{Heat transferred by conduction across the vacuum} = c (\theta_1 - \theta_2) p A \quad \cdots \cdots \quad (6)
\]

It is also known, when \(p\) is measured in mm. of mercury and \(A\) in sq. cms., that \(c\) takes a value for air of approximately \(2 \times 10^{-5}\) at 30°C. To apply equation (6), this figure has first to be adjusted to the average temperature of \(\frac{1}{2} (\theta_1 + \theta_2)\); Table VI has to be consulted for the conduction-loss at any given value of \(\theta_1\), and the latent heat of the liquid mixture in the flask and the dimensions of the flask have to be taken into account. The pressure in the vacuum space, \(p\), can then be computed. It was found in this case to be 0.00039 mm. mercury. Considering that the flask had been evacuated 20 months when the tests were made, this degree of tenacity may be regarded as satisfactory.

**EFFECT of SURROUNDING the 3-litre FLASK by an INSULATING MEDIUM.**

As radiation proved to be the most important cause of evaporation, and/
and as, in radiation between two given surfaces, the temperature of
the hotter surface is the all-important factor, it appeared probable
that evaporation would be appreciably reduced by insulating the flask.

The neck was extended by soldering to it a length of brass tube, and
the whole of the flask, excepting a short part of that tube, was
encased in slag wool in a sheet metal canister. The immediate effect
was an increase in the rate of evaporation; but after the slag-wool
had been given time to cool down its influence became beneficial.
Eventually the rate of evaporation settled to a value that was 82.5
per cent of the rate given at the same external temperature (°C),
when the flask was uninsulated. The increased bulk and clumsiness
of the insulated flask outweighed, from the practical point of view,
any advantage gained.

**THE NECK-LOSS OF LIQUID AIR CONTAINERS.**

Measurements were made to ascertain the temperature gradients
along the necks of four containers for the purpose of finding whether
the relatively great length of the necks (see Fig. 1) was necessary.
Temperatures were taken by means of a Foster pyrometer designed for
low-temperature observation. The wires of the thermo-element were
0.06 in. in diameter. The thermometric scale of the galvanometer was
tested at room temperature, and at that of boiling liquid air, to
ascertain the proportional correction to apply to readings. In
Fig. 3.

TEMPERATURE IN CONTAINER NECKS

PORTION IN PLUG, DOTTED LINE
PORTION IN VACUUM, FULL LINE

GERMAN 50 LBS.
GERMAN 300 LBS.

BOTTOM OF GERMAN 50 LBS.

DISTANCE DOWN NECK, INCHES

-

0 -40 -80 -120 -160 -200°C

TEMPERATURE

M.P.R.C. '20

BOTTOM OF GERMAN 300 LBS.
taking a reading the thermo-junction was lowered to the desired point in the neck and allowed to stay there until the galvanometer needle became stationary. Inasmuch as the thermocouple was in the up-flowing current of cold air, and not necessarily in effective contact with the neck-tube at the point, the temperatures obtained were not strictly those of the metal; the difference, however, was probably not more than a few degrees, and was greatest where it mattered least, namely near the mouths of the flasks.

The results are set forth graphically in Fig. 3.

Three of the bottles were 50-lb. containers of dimensions substantially those indicated by Fig. 1. The fourth was a German-built vessel - the largest vacuum flask in the country - capable of holding over 300 lbs. of liquid air.

The first container examined (see curve labelled "German 50-lb.") Fig. 3 was a brass vessel built and evacuated in Germany before the War. After many years of continuous service at the Newcastle mine rescue station its vacuum was showing signs of break-down; its evaporation rate at the time of the test was 1.65 litres of gas per minute at 10°C, which is equivalent to a daily loss of over 7 lbs. The top of the outer neck was thickly coated with ice. The inner neck was of German silver, 3/8 in. bore, the thickness of the metal being 0.02 in. As Fig. 3 indicates, the neck enters the vacuum space 3 3/4 ins. from the mouth.
The temperature \( \frac{7}{16} \) in. below that point was as low as \(-172{\degree}C.\), and at all parts below \( \frac{47}{16} \) ins. from that point the temperature was the same as that of the liquid in the flask. Under the conditions then obtaining, therefore, the loss due to neck-conduction was nil, and if the neck had been shortened by 5 ins. it would still have been nil.

The second and third containers examined were made in this country and were in satisfactory condition. They were of copper with German silver necks, \( \frac{33}{4} \) ins. long and \( \frac{3}{16} \) in. bore. Their rates of gaseous discharge (measured at \( 16{\degree}C.\) were respectively 1.15 and 1.03 litres per minute at the time of the tests. The curve labelled "L.12 and L.13" Fig. 3 expresses the fall of temperature down the neck for both these flasks. The temperature at the bottom of the necks were, in these cases, appreciably above the temperature of the liquid, a fact which seems to indicate that the evaporated gas gained a little heat from the upper part of the inner globe before it reached the neck in its upward path. With these flasks, the gradient near the base of the neck, though slow, was not zero; a certain amount of heat therefore reached the inner sphere by the neck. The graph indicates, however, that the transference of heat due to this cause was here equivalent to that which would have been yielded by a neck of the same sectional dimensions about 64 ins. long in which the gradient was uniform from top/
The fourth container, as already stated, was a very large German vessel; at the time of testing it was found to be discharging gas at the rate of 3.3 litres per minute, measured at 18°0. It was constructed of brass, with a German silver neck, 24½ ins. long and ⅞ in. bore. The thickness of the metal of the neck could not be determined; the plug (E, Fig.1) probably extended to a depth of about 3½ ins. from the mouth of the bottle. The measurements (see Fig. 3; curve marked "German 300 lbs") show that the passage of heat to the liquid via the neck was zero, and that the rate of evaporation would not have been affected in the least had the neck been half the length.

In general, the results indicate that container necks may be considerably shortened, or both shortened and thickened, without appreciably increasing the rate of loss of the flasks. Such an alteration in construction will strengthen the flask and save weight, and while preserving sufficient flexibility in the neck to allow of the spheres touching during the act of pouring, the excess loss during transportation - which is principally due to the continual bumping together of the cold and hot globes - will be lessened. Underground transport (a matter that the present writer has especially in view) will be facilitated by the reduced height of the bottle.

Results Obtained with Short-necked Containers:— Believing at that time that container necks could be shortened and strengthened without any/
any serious effect upon the evaporation rate, the writer designed, in 1919, a 50-lb. container of which twelve were made and ten proved sound. Though there were, in these bottles, a number of variations upon the "standard" design illustrated by Fig. 1 only two of them could have any influence upon the rate of evaporation. The first of these, namely the provision of a loose, insulated cap to fit over the mouth of the bottle, was found to have only a slight effect: the cap, when in place, only reduced the loss by a few ounces per diem — a fact which itself demonstrated the relatively small heat-inflow by the neck.

The second variation was in the size of the neck, which, in each of these special containers, was of cupronickel (an alloy having about thrice the conductivity of German silver); the bore was $\frac{1}{4}$ in., the thickness of the metal, $\frac{1}{16}$ in. and the length $9\frac{3}{4}$ ins. Had it been possible to disregard the influence of the up-flowing stream of cold air along the neck; that is to say, had neck-loss been merely a question of the conductivity, sectional area and length of the tube for a given temperature-difference, the neck-loss of each of these modified containers would have been 17.5 times that of the German 50-lb. container referred to above. Actually the rates of evaporation of these more robust flasks showed little if any increase upon those of an equal number of container of the usual design, selected at random. Their daily evaporation losses proved to be, respectively, 5.43, 3.75, 4.00/
4.00, 3.75, 3.31, 3.31, 3.62, 3.69, 3.74, and 4.00 lbs.

Acknowledgement is due to Messrs J. Mallinson, B.Sc., W. Cooper, M.A., B.Sc., and J. J. Brodie, Government research workers, for their help in the experiments here discussed. In the tests upon the 3-litre flask, weighings and temperature observations had to be taken at all hours of the night and day for a fortnight.

SUMMARY.

(1) J. A. Harker and his co-workers having shown that of all the possible causes of heat-inflow to liquid air in a vacuum flask only three, viz: radiation, conduction across the vacuum space, and conduction along the neck of the flask are of importance, the writer illustrates by two instances an experimental method enabling these sources of heat-transfer to be separately assessed.

(2) In the two selected instances radiation proved to be the main method of heat-transfer.

(3) In the second example (a 3-litre metal flask) the analysis is carried further, and the emissivity of the surfaces and pressure in the vacuous space are determined. The reasons for the relatively high emissivity are discussed.

(4) Pyrometer measurements in the necks of long-necked large metal storage flasks (containers) showed the loss due to neck-conductin
to be either zero or entirely negligible. The results indicate that the necks of such vessels may be shortened with advantage.

(5) The tranquil evaporation rates are given of ten metal containers having relatively short stout necks, in proof of the foregoing conclusion.