PHYSICAL EXERTION, FITNESS AND BREATHING.¹

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

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.² 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 seventy or eighty 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 thirty pounds. It was observed that an increased oxygen proportion in the air inhaled was uniformly helpful with persons of sedentary habits, but that when working miners were tested little or no such benefit was derived; they 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 specializing in different branch 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.M.G., C.B., and Lieutenant-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. A rate of fifty-six revolutions per minute was adopted throughout. At that speed, and with the gear-ratio of the particular cycle employed, the power expended, in foot-pounds per minute, 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 eight-inch 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 gas being metered were kept under observation.

**Douglas Bag and Sampling Apparatus.**—A sixty-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 three-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 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-feet 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

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1 For long-continued pedalling the pendulum is preferable to the metronome for this purpose; it is less trying to the nerves.
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 direct 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.

![Fig. 1. — Mueller Water Valve.](image1)

![Fig. 2. — Rosling Valve, shut and open.](image2)

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 disk valve so 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 eighty-five litres (three cubic feet) of air per minute is 0·35 inch of water column, and its slip is quite negligible. A not unimportant feature of the rubber valve is its noiseless-
ness. 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.

**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 CO$_2$ 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 three-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 fifty-six revolutions per minute 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 feet pounds per minute, 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 \( \text{CO}_2 \) 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 \( \text{CO}_2 \) output.

The determination of the respiratory quotient 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 sixty. Had that fact been known earlier, the work would have been facilitated by using a mixture containing sixty per cent oxygen and forty per cent 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 sixty-seven per cent 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 contained 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 the 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 three miles per hour 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 makes 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 in-drawn 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 anoxæmia 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 relative 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 CO$_2$ 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 characterized by a fall in the proportion of CO$_2$ expired, the writer feels justified in taking the rate of work corresponding to the maximal CO$_2$ 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 down the scale. Again, the fact that in most cases (e.g. fig. 4) the expired-CO$_2$-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."
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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 foot-pounds per minute, 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 per cent 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 inhales 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 6,000 foot-pounds per minute, for
example, II breathed twenty-four times per minute, while two unusually deep breathers, Nos. XIII and VIII, respired eight times and twelve times per minute 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 per cent and that of VIII was 100 per cent. The factors for the other selected subjects are stated in the Appendix.

The assumption underlying this mode of expressing fitness is twofold: 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 per cent. 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 forty-four per cent; the second time he was well and the factor had risen to eighty per cent; 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 seventy per cent. He was then sent to Aldershot for the final course of training for serjeant-instructors in physical drill and returned to Edinburgh in the “pink” of condition, for further test after being a
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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 per cent. 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 fifty-five per cent; 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 seventy per cent 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 eighty-four men were examined: They were of every medical category, though the "A" class predominated. 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.

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.

**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 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 criticized, though in view of the other sources of error now to be noted small imperfections in those values are barely worth considering. The
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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 realize 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.

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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 respiratory quotient 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 task 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 forty-three pounds. 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 three-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 three-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 parts 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, twenty-five per cent has been added to "C. G. D.'s" oxygen consumptions in the following table to make them more comparable with those of the other men, who were carrying forty-three pounds each.

Tables III, IV and V, derived from the smooth 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 LB.

<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>Standing</td>
<td>Br</td>
<td>Br</td>
<td>Br</td>
<td>Br</td>
<td>Br</td>
</tr>
<tr>
<td>Subject</td>
<td>air</td>
<td>O₂</td>
<td>air</td>
<td>O₂</td>
<td>air</td>
</tr>
<tr>
<td>I</td>
<td>0·71</td>
<td>0·68*</td>
<td>0·77</td>
<td>0·91</td>
<td>1·14</td>
</tr>
<tr>
<td>II</td>
<td>0·47</td>
<td>0·53</td>
<td>0·58</td>
<td>0·59</td>
<td>0·80</td>
</tr>
<tr>
<td>III</td>
<td>0·35</td>
<td>0·41</td>
<td>0·64</td>
<td>0·47</td>
<td>0·90</td>
</tr>
<tr>
<td>XII</td>
<td>0·31</td>
<td>0·28</td>
<td>0·60</td>
<td>0·83</td>
<td>0·88</td>
</tr>
<tr>
<td>XVI</td>
<td>0·35</td>
<td>0·57</td>
<td>0·70</td>
<td>0·84</td>
<td>0·92</td>
</tr>
<tr>
<td>Average</td>
<td>0·40</td>
<td>0·45</td>
<td>0·65</td>
<td>0·69</td>
<td>0·87</td>
</tr>
</tbody>
</table>

C.G.D. (a) 0·40 — 0·60† — 0·84 — 1·14 — 1·47 — 2·65 —
(b) 0·40 — 0·67† — 0·98 — 1·33 — 1·99 — 3·17 —

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

Most economical rate of walking.—Like a steamboat or an airship, a man has a most economical speed at which he goes farthest per litre of oxygen or per pound of fuel or food consumed. The data obtained yielded 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 ninety-nine 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 eighty-two yards. With all the other subjects of Table III—
Physical Exertion, Fitness and Breathing

loaded, as each of them was, with forty-three pounds—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 CO₂-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 expired CO₂-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 CO₂-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 per cent 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 pounds, fitness eighty-three per cent; the position of the "peak load" (7,500 to 8,000 feet pounds per minute) is higher than the average, indicating a man of good stamina.

Subject II (fig. 4).—Sedentary person; weight, 136 pounds; fitness forty-six per cent; 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 pounds; fitness eighty per cent.

Subject IV (fig. 6).—Mine undermanager; weight, 168 pounds; engaged in a mine working flat seams; fitness, sixty-four per cent; oxygen-want becomes serious under 6,000 foot-pounds per minute.

Subject VI (fig. 7).—Army recruit; previously a bank clerk; weight, 142 pounds; fitness, forty-two per cent.

Subject VII (fig. 8).—Regular soldier; weight, 168 pounds; instructor in physical drill; heavy weight lifter; athletic type; fitness, 100 per cent. 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 pounds; fitness, sixty-nine per cent.

Subject XIII (fig. 10).—First-class footballer; runner, jumper and all-round athlete; army instructor in physical drill; weight, 158 pounds. Records were obtained of the subject in three conditions: (1) In good health; fitness, seventy per cent (the ergometer results labelled (A) were obtained on that occasion); (2) in good health and after intensive training at Aldershot; fitness, 100 per cent; and (3) in poor health; fitness fifty-five per cent. 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 pounds; fitness, sixty-three per cent.

Subject XVI (figs. 12, 13).—Research assistant, sedentary habits; weight, 154 pounds.

C. G. D., fig. 14.
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**Figure 3**

**Subject I**

- **Foot-pounds per minute**
  - 3000
  - 6000
  - 9000
  - 12000

- **Litters Oxygen Consumed per minute**
  - 0
  - 10
  - 20
  - 30

**Figure 4**

**Subject II**

- **Foot-pounds per minute**
  - 3000
  - 6000
  - 9000
  - 12000

- **Litters Oxygen Consumed per minute**
  - 0
  - 10
  - 20
  - 30
Fig. 12

Fig. 11
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Henry Briggs

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