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OXYGEN MINE RESCUE APPARATUS AND PHYSIOLOGICAL EFFECTS ON USERS

BY

YANDELL HENDERSON AND JAMES W. PAUL

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PREFACE.

When the United States Government, in 1908, began its investigations of the causes of coal-mine explosions, one of the first subjects to receive notice was the determination of the reliability and practicability of self-contained apparatus for supplying good air to a person surrounded by suffocating or poisonous gases. Several types of such apparatus were in use or being introduced at mines abroad, but were not in use in the United States. The mine-accident investigations conducted by the Government in 1908 and 1909 and the prominence given mine rescue training and equipment by the Bureau of Mines during the past five years have resulted in the wide adoption of oxygen breathing apparatus not only at mines, but at manufacturing establishments, on shipboard, and by municipal fire departments.

The value of such apparatus has been demonstrated so many times as to leave no doubt, but as yet comparatively little fair and authoritative information has been published regarding the relative merits of different types of breathing apparatus and the defects of all types now in use. The main purpose of the present report is to supply such information. Dr. Yandell Henderson, professor of physiology in the Yale Medical School, and consulting physiologist in the Bureau of Mines, is a recognized authority on the physiology of respiration; J. W. Paul, formerly chief of the department of mines of West Virginia, was in charge of the mine rescue work of the Federal Government from 1908 to the end of 1915 and has had unequalled facilities for studying the use of breathing apparatus.

This report has three purposes: First, to show the inherent limitations of present types of oxygen breathing apparatus and to indicate improvements in design that will more nearly meet the requirements of use in poisonous or irrespirable gases; second, to explain how by relatively slight changes of adjustment the present types of apparatus may be made more efficient and much safer; and, third, to present the results of practical tests and of actual use of breathing apparatus. The authors have thus cooperated from the points of view of the physiologist and of the engineer in the accumulation of material, and in theoretical and practical tests of the conclusions reached.

The general conclusions are largely the results of tests conducted by or under the direction of Dr. Henderson. They present the physiological requirements that should govern the design, construction and use of oxygen breathing apparatus, and offer critical comments on the present types of apparatus. Most of the physiological tests were conducted at the Pittsburgh experiment station of the Bureau of Mines. In the conduct of these tests especially valuable assistance was rendered by G. A. Burrell. He and C. G. Storm, both chemists of the bureau, made many analyses of air samples and of alkaline absorbents for CO_2. Other members of the bureau's staff, especially L. M. Jones, G. H. Deike, J. T. Ryan, W. J. German, W. A. Raudenbush, H. D. Mason, jr., G. E. McElroy, E. H. Denny, and H. D. Jones, also assisted in the tests or acted as subjects for tests.

The report deals with rescue apparatus also from the standpoint of an engineer and treats of its practical use in rescue work. During seven years, until January, 1916, Mr. Paul was in charge of the mine rescue operations, the testing of the various types of apparatus, and the selection, for the equipment of the rescue operations of the Bureau of Mines, of those types shown to be best suited for rescue work. His experience has included the supervision of many mine rescue contests in which the apparatus was worn, as well as the personal direction of many actual rescue operations following mine disasters. Thus he has been enabled to discover in actual practice the defects as well as the merits of the various types of apparatus.

The results of tests with the present types of apparatus in the smoke room, in the open air, and in mine rescue work and maneuvers demonstrate the necessity of training in accordance with a definite schedule of work. Without such training the limitations of present forms of apparatus can not be appreciated by men who may be called on to wear them, and without such knowledge a wearer may endanger his life in attempting to exert himself unduly. Consequently, the continuation of careful training in noxious gases under conditions similar to those found in mines is essential, and the practice of conducting in the open air tests involving great physical exertion and large oxygen consumption, at least for brief periods, is scarcely less important.

Until improved types of apparatus are made in which the temperature of the inspired air is under better control, the carbon dioxide of the breath absorbed with greater efficiency, and a variable volume of oxygen automatically supplied, present types of oxygen rescue apparatus must be used, in spite of their limitations. It is to be expected, however, that the publication of this report will lead to early and marked improvements, for it makes available to inventors and manufacturers the physiological information essential to the construction of better types of apparatus. It also shows the purchasers of apparatus the qualities requisite for efficiency and reliability and the methods of testing these qualities; and will thus lead the users of apparatus to an intelligent demand for improvement in the instruments upon which their lives depend.

As the most effective means of putting into concrete form and of testing the feasibility of the recommendations of this report, the Bureau of Mines has attempted to develop an apparatus along the physiological lines for which it calls. During the past two years W. E. Gibbs, an experienced mechanical engineer, has been at work for the bureau on this problem. Mr. Gibbs, aided by the advice and cooperation of the authors of this report, has produced an apparatus which, in experimental tests, has shown itself superior to the older types, but which has still to be subjected to further tests in service. Its principal features have been patented for the Bureau of Mines, and, if finally successful, will be made available for general use.

Van. H. Manning.

OXYGEN MINE RESCUE APPARATUS AND PHYSIOLOGICAL EFFECTS ON USERS.

By Yandell Henderson and James W. Paul.

IMPORTANCE OF SAFE AND EFFICIENT RESCUE APPARATUS.

Self-contained breathing or rescue apparatus, often popularly referred to by the simple but misleading term "oxygen helmet," is a device by which man is enabled to do work in places where he is by nature unfitted to go, to live, and to work. In this respect mine rescue apparatus may be classed with the aeroplane and with diving apparatus, including the submarine boat. The loss of life that has attended the development of the aeroplane and the submarine is well known; the loss of life in the development of oxygen apparatus for use in asphyxiating gases is not so generally realized. That such development is accompanied by fatalities is not surprising, because penetrating the smoke-filled passages of a burning mine is quite as abnormal as for man to ascend into the air or to navigate and explore the water below the surface of the sea.

Mine rescue apparatus differs from the aeroplane and the submarine in the character of the obstacles to be overcome in developing safe and efficient types. The two latter devices have to meet difficult physical conditions to achieve equilibrium and propulsion, which are essentially engineering problems. Fitting the devices to the human passenger is a comparatively small part of the problem. In developing mine rescue apparatus the real problem is not only to make an efficient and reliable device but also to fit it to the peculiar and varying needs of the wearer. Improvement in rescue apparatus has been slow, because of the fact that it was devised and studied chiefly by engineers. Until recently, when the investigations reported here were undertaken for the Bureau of Mines in this country, and similar investigations reported by Dr. J. S. Haldane were made in England, there had been no adequate study of apparatus from the standpoint of the physiologist. Experience had demonstrated defects, but had not explained their underlying causes.

The principal literature on this general subject is as follows:

Hagemann, —. Bergmannische Rettung und Feuerschutzwesen.

Draeger, Bernhard, The historical development of rescue apparatus, Lübeck, 1911.

Stassart, S., and Bolle, J., Les appareils respiratoires et la station de sauvetage de Frameries: Ann. des Mines de Belgique, ser. 1, t. 14, 1909, pp. 519–706.

Cadman, J., and others, Report of the Mine Rescue Experimental Committee of the South Midland Coal Owners, Birmingham (England), 1911.

Boycott, A. E., Haldane, J. S., and others, First Report of the Royal Commission on Mines, London, 1907, 52 pp.

Haldane, J. S., Self-contained rescue-apparatus for use in irrespirable atmospheres; report to the Doncaster coal owners (gob-fire research) committee: Trans. Inst. Min. Eng., vol. 47, pt. 6, 1914, pp. 725–776; vol. 48, 1915, pp. 550–595.

Zuntz, N., and Schumburg, —, Studien zu einer Physiologie des Marsches, Berlin, 1901, 361 pp.

Benedict, F. S., and Cathcart, E. P., Muscular work; a metabolic study with special reference to the human body as a machine: Carnegie Inst. Washington, 1913, 176 pp.

Benedict, F. G., and Murschhauser, Hans, Energy transformations during horizontal walking: Carnegie Inst. Washington, 1915, 100 pp.

Carpenter, T. M., A comparison of methods for determining the respiratory exchange of man: Carnegie Inst. Washington, 1915, 265 pp.

Like all animals, man is by nature accurately adjusted to his normal environment, and of this environment no features are more essential to life and activity than those of the atmosphere. It is important, therefore, if a man is to wear breathing apparatus for even a few minutes and essential if he is to depend on it to keep him alive for several hours and is to do considerable work, that the conditions in his lungs should be essentially similar to those in breathing normal air. The apparatus must adjust itself to the respiratory needs of the wearer and also to wide variations in these needs. Until recently, however, the wearer has been expected to adjust his breathing to the apparatus. To forget and fail to do this for even a few minutes might cause his death.

Thus, as an instance of only one of several grave defects in the apparatus now chiefly used, the manufacturers of rescue apparatus have usually directed that the oxygen supply should be set at a rate sufficient only for moderate exertion on the part of the wearer.

Because of such defects rescue crews have been trained to walk slowly and to stop and rest at frequent intervals. If the roof were to give way or if for any other reason immediate escape from a mine became necessary, a rescue crew would indeed be "between the devil and the deep sea." To move slowly might mean to be crushed, whereas a vigorous attempt to escape would result in collapse or even asphyxiation because of insufficient rate of oxygen supply. It is scarcely necessary to add that no amount of preliminary training can prevent a man from choosing instinctively the latter alternative and attempting to escape. It is evident also that this defect in apparatus can be easily remedied by applying well-established physiological facts regarding the amount of oxygen that a man vigorously exerting himself may consume.

Breathing apparatus is being generally introduced. Some States even require by law its purchase by mine owners. A large number of coal and metal mines in this country now have apparatus on hand for use after explosions or mines fires. Breathing apparatus is also being sold in increasing amounts to the fire departments of cities, and crews have been trained to penetrate smoke-filled buildings for the saving of life and property. Around gas works and refrigerating plants air helmets of a simple type are sometimes very useful. Breathing apparatus finds also a use in the Navy when the deeper and unventilated compartments of a vessel are to be entered. The recent introduction of asphyxiating gases for offensive military purposes has been met by means of simple masks provided with a chemical absorbent. It is reported also that, on one side at least, the men setting off the gas are themselves protected from asphyxiation by means of oxygen mine rescue apparatus of the so-called "half-hour" type.

The authors have approached the study of breathing apparatus from two standpoints. One of the authors is a physiologist and has brought to bear on the problem scientific knowledge regarding the amount and character of the air that a person needs to maintain life and activity, as well as technical experience with breathing apparatus as used in physiological laboratories for purely scientific purposes. The other is a mining engineer who for several years past has had charge of the training and mine rescue and recovery work of the rescue crews of the Bureau of Mines, and has thus learned from extensive experience the capabilities and the defects of the types of apparatus now in use. From both standpoints it has been found that the wearing of these types involves grave danger, owing to the fact that the makers have as yet failed to meet satisfactorily certain mechanical and physiological needs in construction. It is equally clear that comparatively small changes in the present forms of apparatus would considerably reduce these dangers.

The authors are aware that many practical mining men who have used mine rescue apparatus may take exceptions to these statements. It is a striking fact that men trained in the use of such apparatus usually develop great confidence in it. It is not unusual for a practical mining man or a member of a city fire department, when told of the dangers and defects of the apparatus to which he has become accustomed, to insist that his own experience contradicts these criticisms.

The suggestions made in this report for improving present types of apparatus have as far as possible been incorporated in the practice of the rescue crews of the Bureau of Mines for at least a year and in some cases for several years past. They are the result therefore not merely of theory and experiment but of actual experience in service. The manufacturers of apparatus and their agents have from time to time been informed of defects found and of improvements desired by the bureau. Owing to these suggestions, and to similar and exceedingly valuable investigations and recommendations made recently by Haldane[a] in England for the Doncaster coal owners, there have of late been marked improvements in respect to a number of the features of the apparatus put upon the market. The manufacturers have shown themselves in most cases willing and anxious to make every possible improvement. The better his apparatus, the greater are a manufacturer's sales, and in the long run the larger his profits.

The one notable exception to this desire for improvement is in respect to the helmet, which forms a part, although not an essential part, of some of the best known apparatus. The Bureau of Mines discarded the helmet for its rescue crews some years ago. As the following pages show, it is one of the most objectionable and most easily eliminated defects of the apparatus now in use.

Among reported deaths in this country of persons wearing apparatus, all the victims except two were using helmets. It is probable that most of the breathing apparatus now being sold in America includes this device. The fire department of the city of New York has recently organized a rescue crew and equipped it with apparatus including helmets. In fact, the helmet is so striking in appearance and makes so forcible an appeal to popular imagination that magazines reproduce photographs of rescue crews so equipped carrying an injured man to safety—an exertion of which men hampered with helmets are practically incapable. The newspaper reports of mine accidents and city fires in which rescue apparatus has been used begin almost invariably with "the arrival of the men with oxygen helmets."

Furthermore, miners and firemen and even mine superintendents and engineers who have not been shown the disadvantages of the helmet by means of such tests as the Bureau of Mines now applies usually prefer the helmet to the mouth-breathing form of apparatus. Recently the agent of one of the principal companies manufacturing helmets stated to one of the authors that he realized the disadvantages of the helmet, but that his customers demanded helmets, and

[a] Haldane, J. S., Self-contained apparatus for use in irrespirable atmospheres, report to the Doncaster coal-owners (gob-fire research) committee: Trans. Inst. Min. Eng., vol. 47, pt. 6, 1914, pp. 725, 776; vol. 48, 1915, pp. 550–595.

if he did not supply them they would obtain apparatus so equipped from his competitors. One of the objects of this paper is to make available to purchasers of breathing apparatus such information as will effectually end the demand for helmets, at least in their present form.

THE PRINCIPAL TYPES OF RESCUE APPARATUS.

At the present time the apparatus sold in North America consists mainly of three types: The Fleuss or Proto, manufactured by Siebe Gorman & Co., of London, England; the Draeger, manufactured by the Drägerwerk, Lubeck, Germany; and the Westfalia, manufactured by the Armaturen- und Maschinenfabrik " Westfalia ", Gelsenkirchen, Germany.

In their broadest features these three forms of apparatus are identical. Indeed, it is probable that, failing some important scientific discovery, such as, for instance, some chemical substance which could be used in a simple respirator to absorb carbon monoxide from the inhaled air, all future apparatus will have to be built on fundamentally similar lines. It is in details that improvements are especially needed in order to replace danger with safety. The main features of the apparatus consist in (*a*) a rubber bag or bags into which and from which the wearer breathes, (*b*) a steel cylinder or cylinders containing compressed oxygen which feeds into the bag through a reducing valve, and (*c*) several pounds of sodium hydrate or other alkali in the form of sticks, granules, or plates, carried either in the rubber bag or in a metal box connected with it, which absorbs the carbon dioxide exhaled.

It would seem at first glance that the ideal apparatus would be one in which enough compressed air or oxygen could be carried so that no rebreathing would be necessary. Some attempts have indeed been made to utilize liquid air in this way. In ordinary breathing, however, a man inhales and expires anywhere from 6 or 7 liters of air per minute during rest, up to 60 or 70 during vigorous physical exertion. It appears utterly impossible, on account of the weight of the air and necessary containers, for a man to carry with him either in compressed or liquid form such a supply as will enable him to have entirely fresh air at each breath for any such length of time as breathing apparatus is worn in mine rescue operations. For service up to a maximum of 10 minutes a compressed-air apparatus could probably be devised and might be serviceable, although it would probably be rather heavy and expensive. Practically the only feasible arrangement of apparatus for longer service appears to be, as already indicated, one in which the subject continually breathes into and rebreathes from a bag or bellows an atmosphere in which the oxygen is replaced as he consumes it and from which the carbon dioxide is absorbed as he exhales it.

An apparatus has been invented in which the oxygen consumed by the wearer is supplied from a vessel containing liquid air. Aside from the cooling effects of liquid air on the apparatus this arrangement has no particular advantages, but a number of disadvantages as compared with compressed oxygen. The rate at which liquid air can be volatilized and supplied to the wearer of the apparatus is much less easily controlled than is the flow from cylinders of compressed oxygen. Liquid air can not be stored for any great length of time, and machinery for its production is not usually available near mines.

Attempts have also been made to devise an apparatus in which sodium or potassium peroxide (oxylith or oxone) would be used both as the source of the oxygen and as the medium for absorbing the carbon dioxide exhaled. This method is attractive in theory, but in practice has a number of disadvantages for anything more than a short-service apparatus. Among these may be mentioned the great amount of heat produced when oxygen is liberated from sodium peroxide by water vapor or carbon dioxide, the foaming of the material and resulting blocking of the air ducts, and also the fact that sodium peroxide mixed with coal dust is explosive.

Because of these facts no attempt will be made in this report to discuss the particular features of the types of apparatus constructed to use liquid air or sodium peroxide. There is the less need for such a discussion here because of the fact that a critique of these forms of apparatus has recently been published by Haldane,[a] in England, who found, for instance with the "pneumatogen," a sodium and potassium oxide apparatus, that the resistance to respiration was excessive, and with the "aerophor," a liquid-air apparatus, that the rate of evaporation was insufficient to supply a man making even moderate exertions with the required volume of air per minute, although it afforded a wastefully excessive amount of oxygen.

Even as regards the three forms of apparatus most commonly used in America, it is scarcely worth while in this report to make detailed criticisms of particular features. A new model is brought out every few years, rendering the older forms obsolete. Most of these models have been thoroughly discussed by Dr. Haldane. It has seemed to the authors, therefore, that it would be advantageous to set forth the features that any breathing apparatus must have in order to be safe and efficient in supporting the respiration of an active man. This report deals with the particular features of the apparatus now in use only in so far as they illustrate the incorporation of technically correct principles and construction or the reverse. It is hoped

[a] Haldane, J. S., Loc. cit.

in this way to afford purchasers of apparatus information regarding what constitutes a safe and reliable form and how safety and reliability may be tested; to set up for manufacturers standards that they should strive to attain; and possibly also to stimulate inventors to the devising of improved types.

Impelled largely by the observations given herein the Bureau of Mines has also undertaken to develop an apparatus that should embody its recommendations. W. E. Gibbs, a mechanical engineer of experience and skill specially suited to this task, has during the past two years been at work for the bureau on this problem, with the advice and assistance of the authors. He has so far succeeded that the essential features of the new Gibbs apparatus have now been patented by the bureau for the benefit of the public. Some work is yet to be done to make the apparatus suitable for service conditions, chiefly in perfecting minor details. Also it must be subjected to continued practical usage in mines by rescue corps to insure mechanical durability and efficiency under these conditions before it is officially approved by the bureau. In the essential features—the supply of oxygen, the absorption of carbon dioxide, and the elimination of objectionable heat—it has been found to meet physiological requirements. In recent tests, in which it was compared with the forms of apparatus in general use, the opinion of the miners who wore it was that it "gives the best air they ever had." The principal features of the three forms of apparatus mentioned, and the particular features of the Gibbs apparatus, are described in the following pages.

THE FLEUSS OR PROTO.

The Fleuss or Proto apparatus (fig. 1 and Pl. I) is decidedly the simplest that has yet been invented. The cylinders of compressed oxygen are slung over the small of the back. Closely connected with them is a reducing valve which is set to afford a definite flow of oxygen, usually about 1,800 c. c. per minute. There is also a by-pass, controlled by a separate stopcock, by which the large rubber breathing bag can be rapidly inflated. The oxygen supply both from the reducing valve and the by-pass flows through a tube under the wearer's arm to the breathing bag, which is suspended over the chest and abdomen. This bag has a partition of heavy sheet rubber extending down from the top to within a short distance of the bottom. Flexible rubber tubes connected with the upper corners of the bag lead to a mouthpiece. A nose clip compresses the nostrils and the wearer breathes wholly through the mouth. Valves are placed at the junctions of the tubes with the bag so that he inhales from the bag on one side of the partition and exhales into the other side.

Four to six pounds of caustic soda in sticks is placed in the rubber bag. When the apparatus is put on, the bag is inflated with oxygen by means of the by-pass. Thereafter the wearer's breath passes into the bag and down through the caustic soda, and is reinhaled from

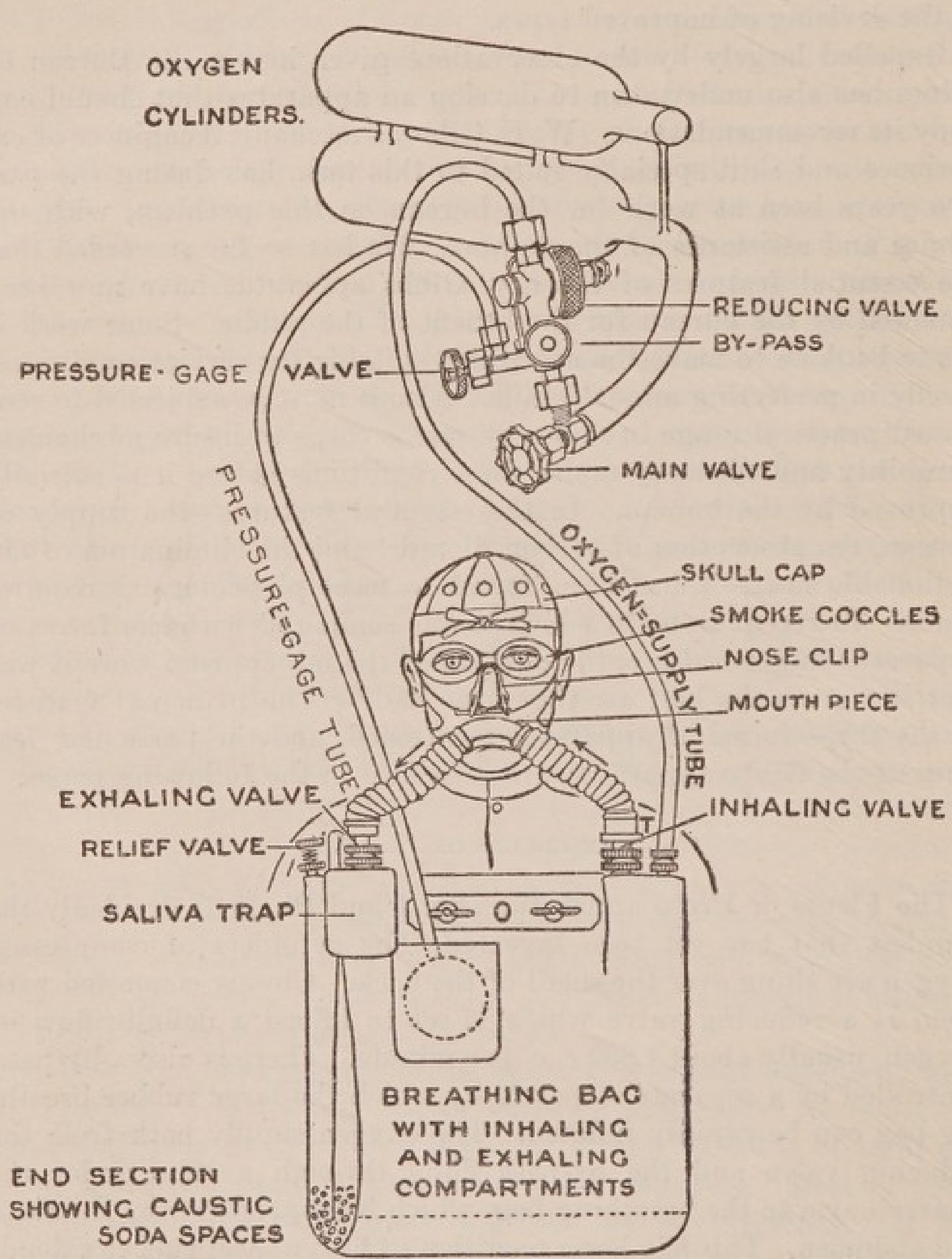
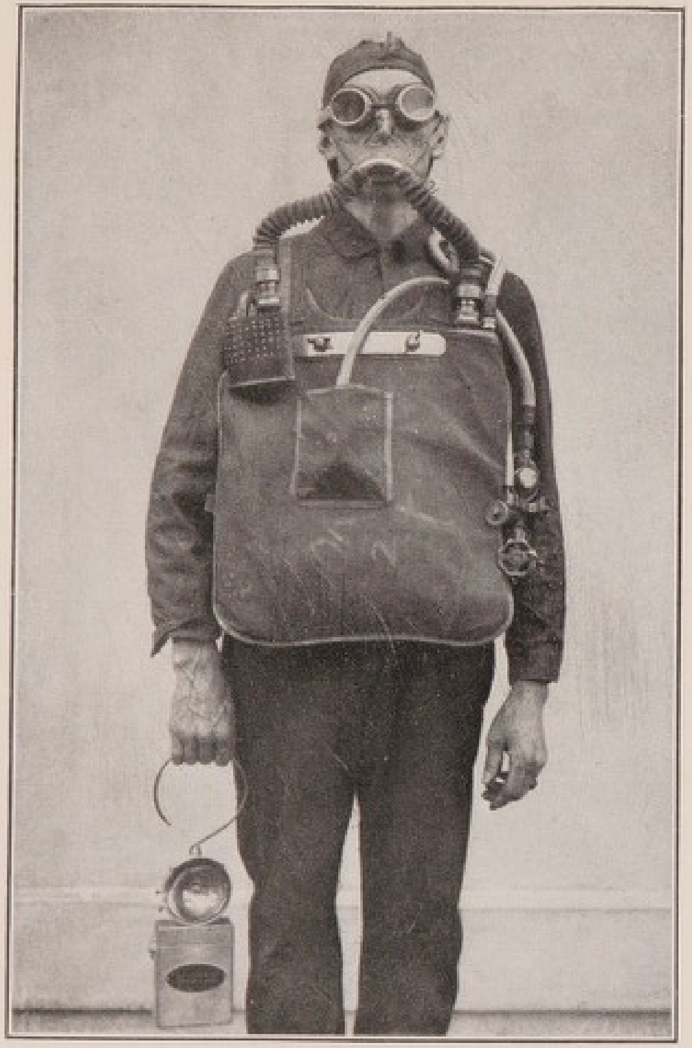
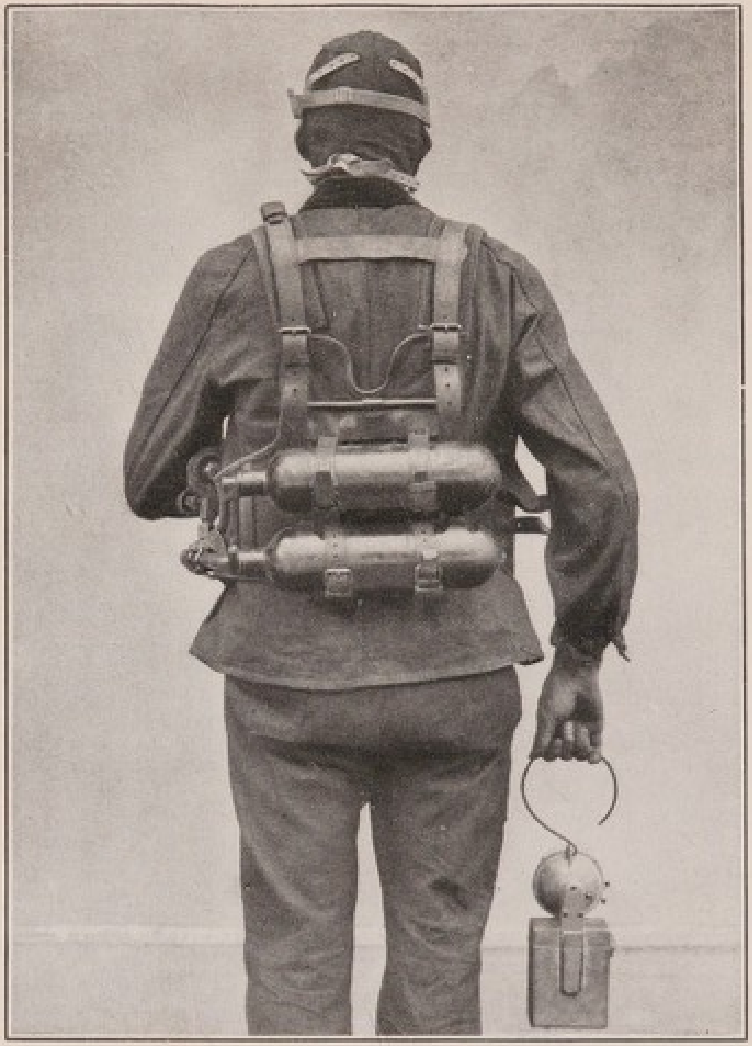


FIGURE 1.—Circulating system of Fleuss, or Proto, apparatus.

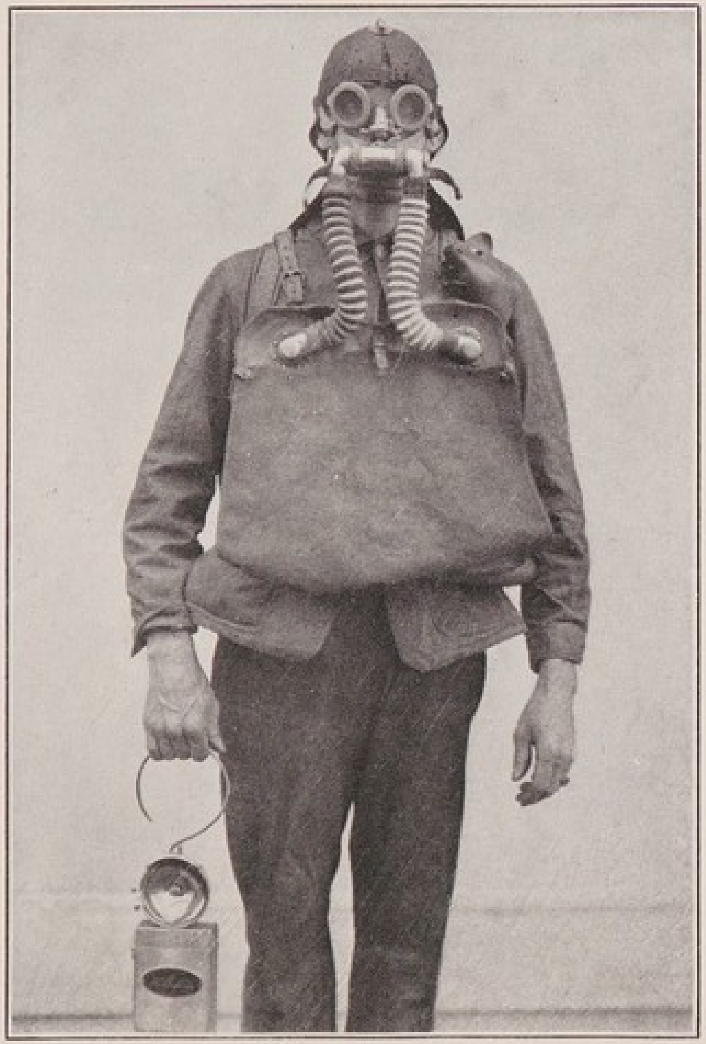
the other side of the partition. Carbon dioxide is thus absorbed, while oxygen is continually flowing in from the reducing valve. The efficiency of absorption may be increased by shaking the bag and thus knocking the accumulated carbonate off the sticks of sodium hydrate, so as to present a fresh surface for absorption. Numerous



A. FLEUSS OR PROTO TWO-HOUR BREATHING APPARATUS.



B. FLEUSS TWO-HOUR APPARATUS, BACK VIEW.



A. DRAEGER TWO-HOUR APPARATUS, MODEL 1912, FRONT VIEW.

B. DRAEGER TWO-HOUR APPARATUS, MODEL 1912, BACK VIEW.

analyses of the air from this form of apparatus have shown that except when the wearer is resting the bag should be shaken frequently; otherwise the carbon dioxide accumulates and makes breathing uncomfortable.

THE DRAEGER AND THE WESTFALIA.

For the purposes of this report the Draeger (Pl. II and fig. 2) and the Westfalia (Pls. III, IV, and fig. 3) apparatus may be considered as essentially similar to each other, at least in their main features. A single description will therefore do for both, and will bring out the points in which they differ from the Fleuss. Reference to

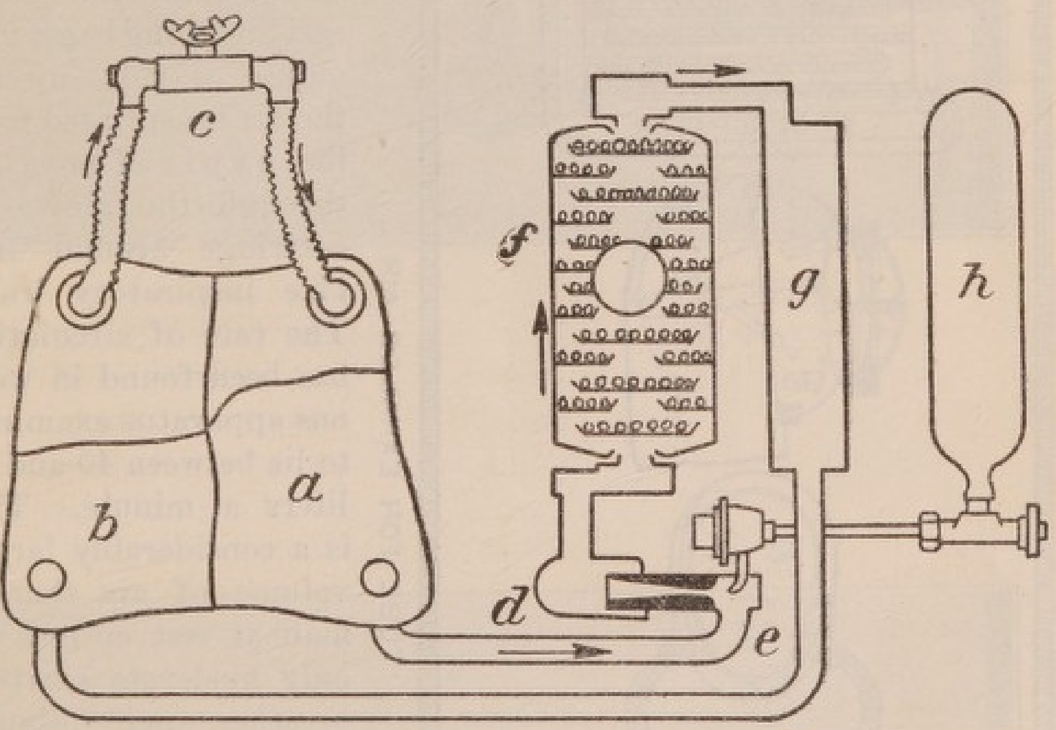


FIGURE 2.—Circulating system of Draeger positive-pressure apparatus. *a*, exhalation bag; *b*, inhalation bag; *c*, mouthpiece; *d*, tube to injector; *e*, injector; *f*, carbon-dioxide absorber; *g*, cooler; *h*, oxygen container.

figures 1, 2, and 3 will help to make this description clear. As both the Westfalia and Draeger have appeared in a number of different models from year to year, for brevity the following description particularly applies to one of the older models of the Draeger, which has been widely sold, and which in some respects is less dangerous than the more recent models. In this apparatus the breathing bag, which is carried upon the chest, has two compartments; from one the wearer inspires, into the other he expires; the tubes and valves leading to the mouthpiece, or the helmet, being so arranged in this model that the air can pass only in one direction. The alkali for the absorption of carbon dioxide is not, however, in any of the Westfalia or Draeger models placed in the breathing bag, but is contained in a cartridge of sheet metal in which granules of alkali are carried in small trays or upon wire gauze, so as to be exposed to the air that passes through the cartridge.[a] The passage of air through this cartridge does not depend on the wearer's breathing; an artificial circulation is caused by an injector through which the oxygen compressed in the steel cylinders carried on the wearer's back feeds into the tubes and breathing bags. By means of this injector the air is aspirated from the expiratory bag through the absorbing cartridge around into the inspiratory bag. The rate of circulation has been found in various apparatus examined to lie between 40 and 70 liters a minute. This is a considerably larger volume of air than a man at rest or making only moderate exertion breathes per minute. In theory the apparatus, aside from the dead space of the helmet, is properly designed for a man's needs under these conditions. But should the wearer exert himself and should his rate of breathing exceed the circulation afforded by the injector, he would be unable to fill his lungs because of the inspiratory bag being sucked flat at each breath. To avoid this in the Draeger there is an opening between the

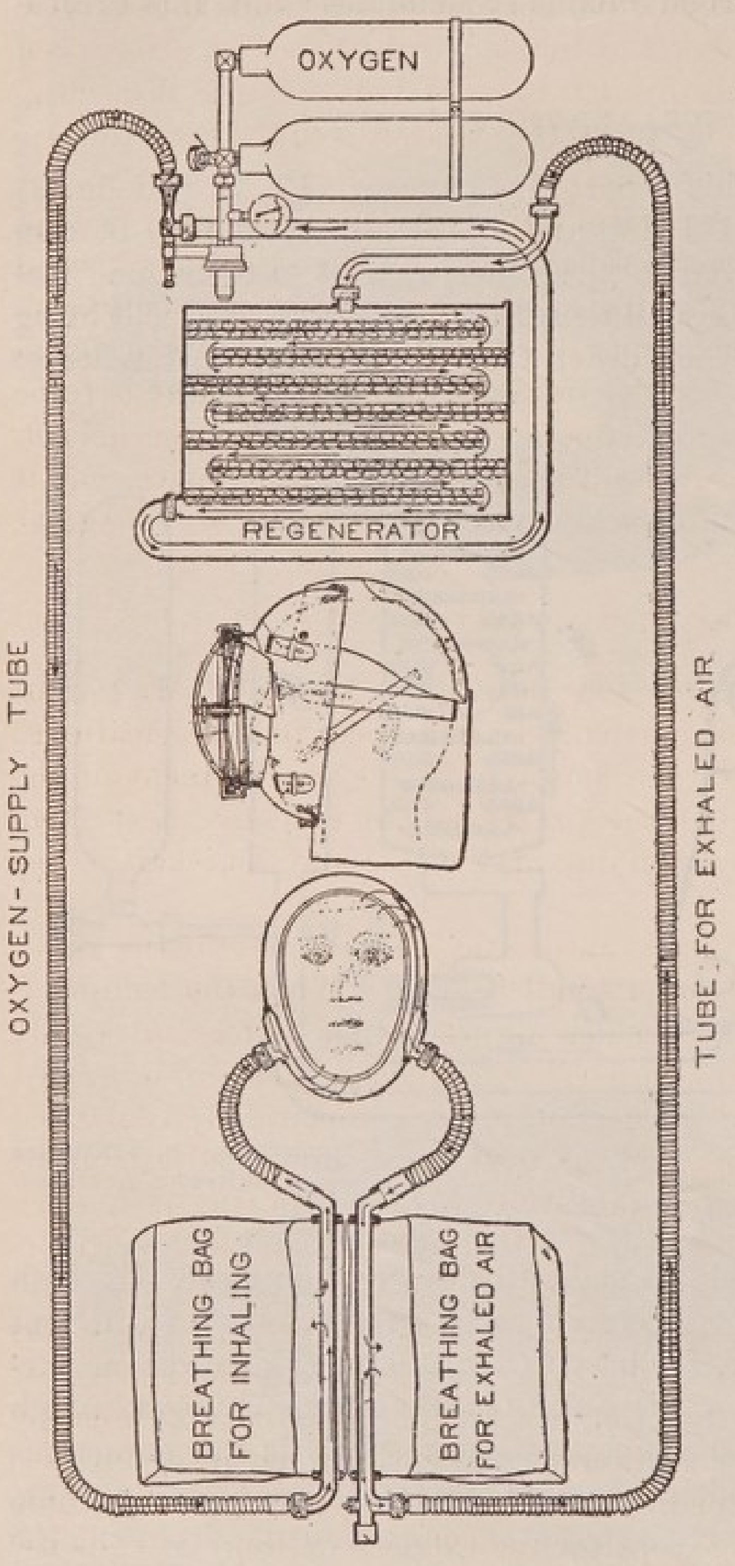
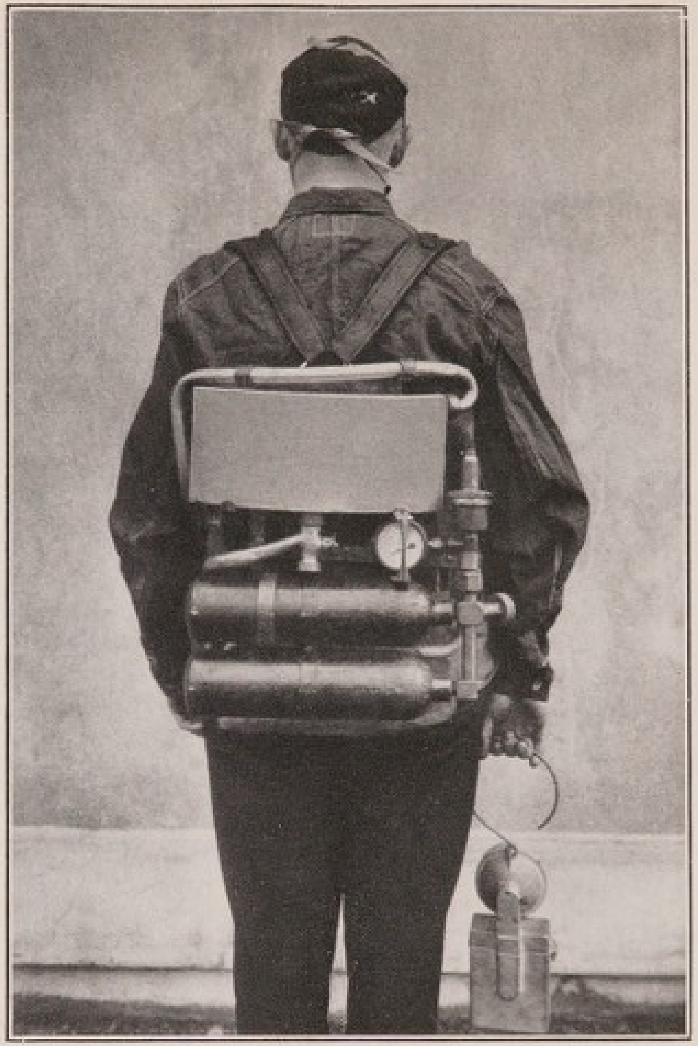


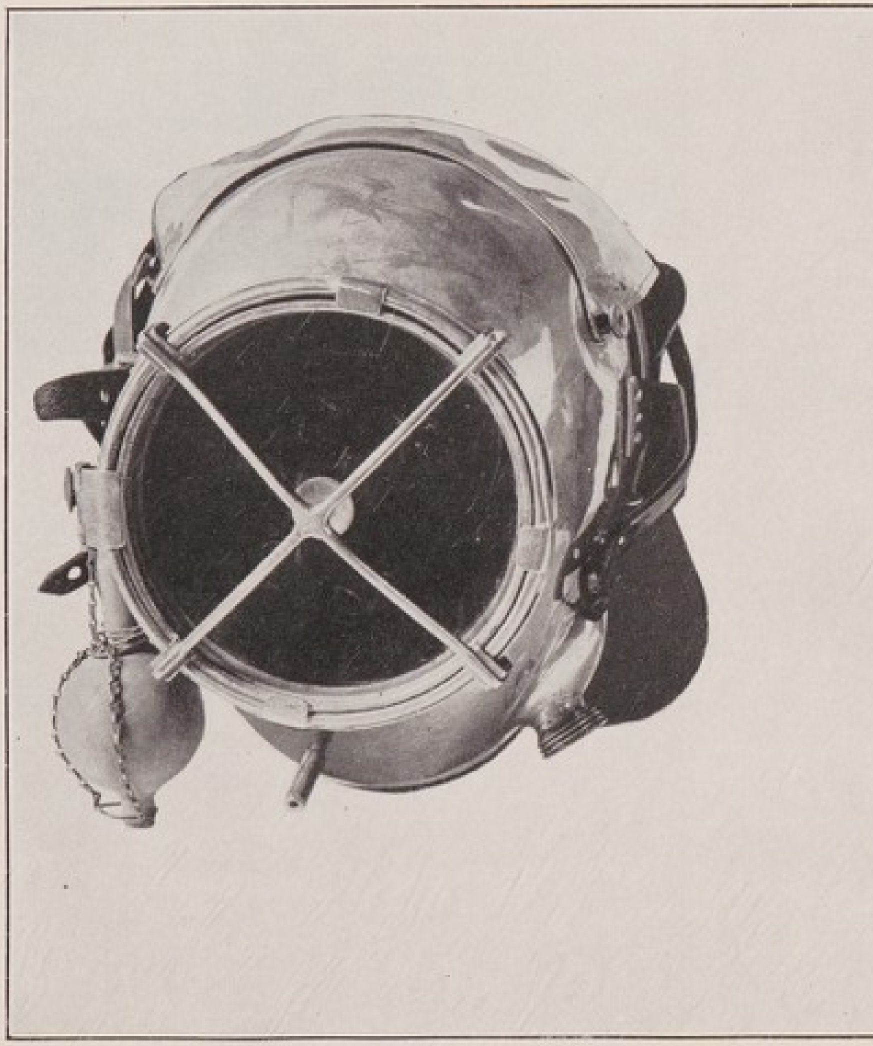
FIGURE 3.—Circulating system of Westfalia helmet apparatus.

[a] These cartridges are called "potash cartridges," although the alkali with which they are loaded is chiefly caustic potash, and those recently manufactured in this country employ only caustic soda. Soda is in fact superior to potash for this particular purpose.

A. WESTFALIA TWO-HOUR APPARATUS, FRONT VIEW.



B. WESTFALIA TWO-HOUR APPARATUS, BACK VIEW.



WESTFALIA HELMET.

DRAEGER HELMET.

inspiratory and expiratory bags. By means of this opening, however, when the volume of air breathed by the wearer exceeds the automatic rate of circulation of the apparatus, a considerable volume of expired air is drawn back and inhaled with the air that has been purified by being aspirated through the cartridge. In the Westfalia, which has no valve in one tube, the wearer would rebreathe air directly from the exhalation bag.

The Draeger and the Westfalia apparatus are sold either with a mouthpiece or with a helmet. The Fleuss, on the other hand, until recently has been sold only with a mouthpiece. Recently a face mask has been supplied with this apparatus when desired, and is designed especially for use in city fire departments, where great heat is to be faced. It is free from the particular disadvantages of the helmet, because it has not the large dead space of the latter device, but it hinders vision and, like all such devices, it is liable to the great danger of leakage.

THE GIBBS APPARATUS.

The apparatus devised for the Bureau of Mines by Mr. Gibbs differs from the foregoing particularly in respect to three features: (1) The control of the oxygen supply, (2) the arrangement of the alkaline absorbent, and (3) the prevention of excessive heat from the reaction between the carbon dioxide exhaled and the alkali. (See Pl. V and fig. 4.)

The rate of oxygen supply is automatic. The wearer of the apparatus breathes into and from a small bellows. When the bellows is sucked flat a valve is opened, which allows oxygen to feed in rapidly from the compression tank through a reducing valve of improved design. Thus, the rate of oxygen supply is automatically controlled by the wearer's breathing, and, as tests have shown, adjusts itself with equal readiness and adaptability to his needs during rest, when the consumption per minute is only 300 or 400 c. c., and during vigorous exertion, when it is between 2,000 and 3,000 c. c. per minute.

The device for the physiological control of the oxygen supply was worked out by Mr. Gibbs at the suggestion of the senior author of this report, who in turn drew the idea from an apparatus devised by Haldane and Douglas, for a different and entirely scientific purpose, during the Pikes Peak expedition.[a] The device would not be feasible in mine rescue apparatus except for the extreme delicacy of response and the reliability of the Gibbs reducing valve. The Weg, an English apparatus not sold in this country, has an automatic oxygen feed valve, but it is of the ordinary differential type.

[a] Douglas, C. G., Haldane, J. S., Henderson, Y., and Schneider, E. C., Physiological observations on Pikes Peak: Phil. Trans. Roy. Soc. London, vol. 203, 1913, p. 35.

The movement of air in this apparatus depends on the breathing, as in the Fleuss type, and not on an injector, as in the Draeger and Westfalia types. From the mouthpiece the expired air passes

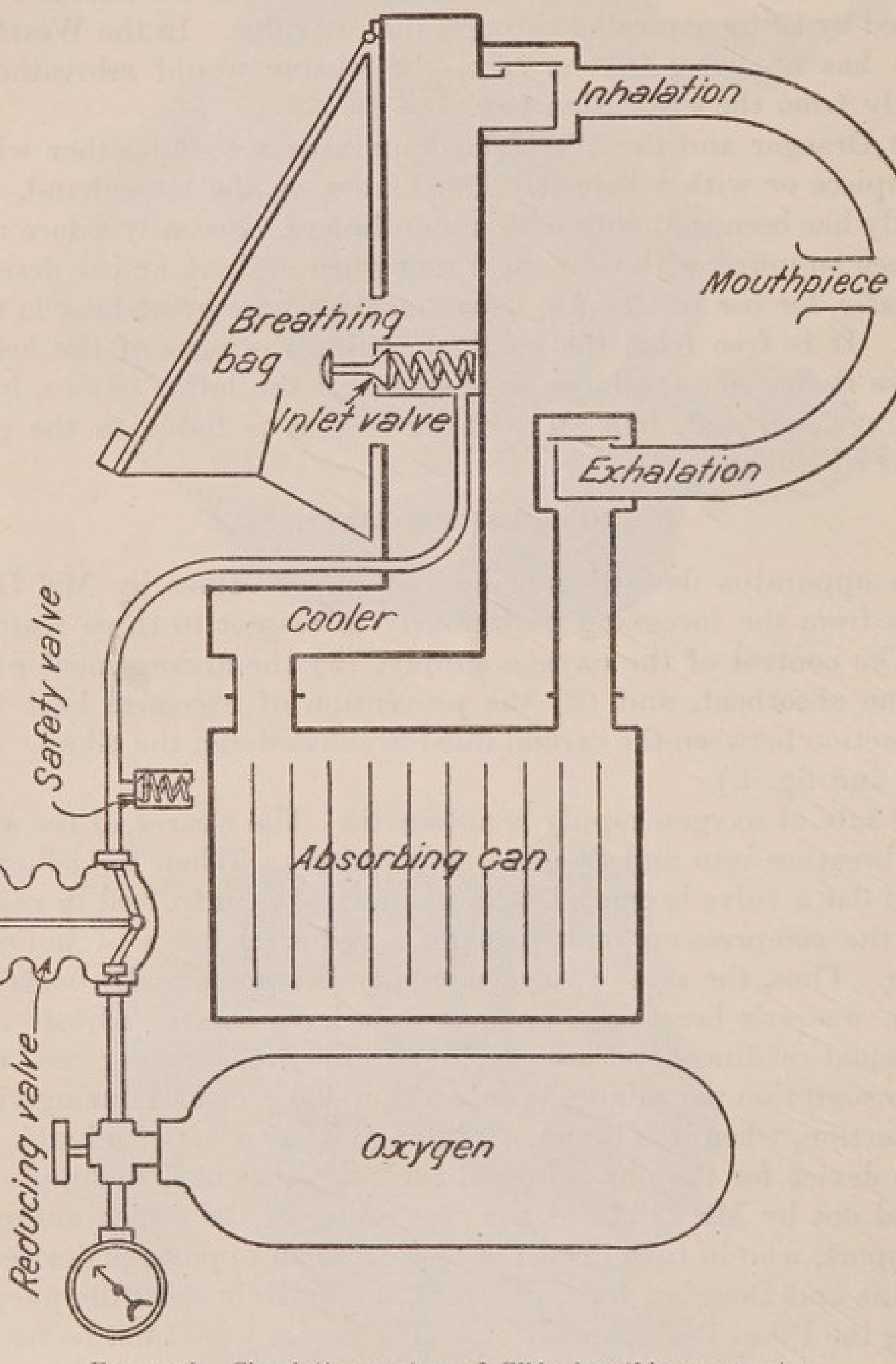
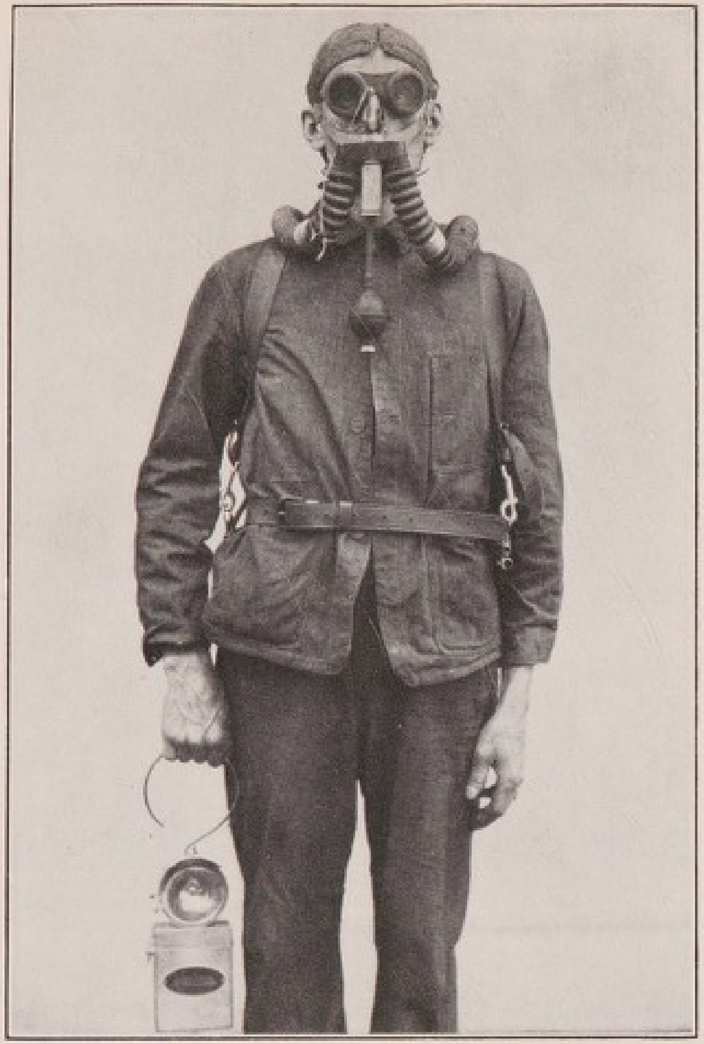
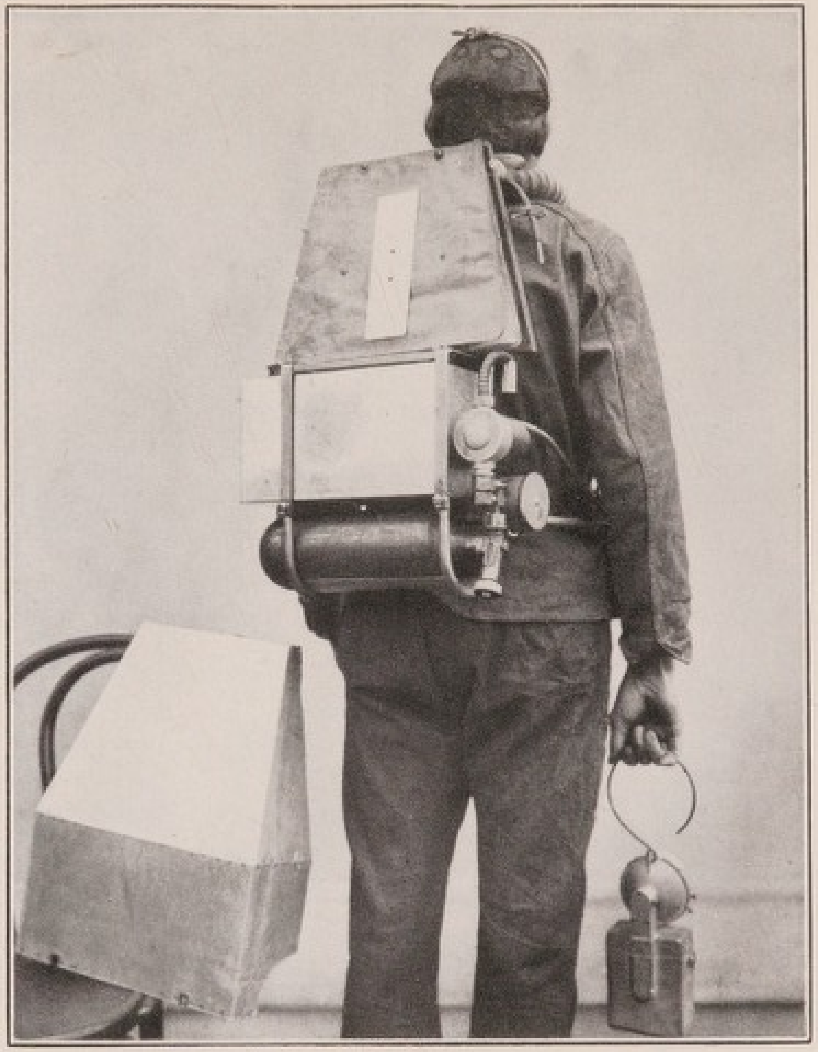


FIGURE 4.—Circulating system of Gibbs breathing apparatus.

through a cartridge somewhat similar to that of the Draeger and the Westfalia; the sodium hydroxide is, however, cast in plates upon wire gauze. At the suggestion of the senior author of this report,



A. GIBBS TWO-HOUR APPARATUS, FRONT VIEW.



B. GIBBS TWO-HOUR APPARATUS, BACK VIEW. (COVER REMOVED).

trial has been made, instead of fused alkali, as in the Fleuss, Draeger, and Westfalia types, of alkali containing a small percentage of water of crystallization, approximately 19 per cent, or one molecule of water to two of sodium hydrate. The avidity of the alkali for moisture is thus already partly satisfied, so that the amount of heat produced is considerably less than in other forms of apparatus, and the alkali is efficient at a much lower temperature.

Recently trial has also been made of an absorber somewhat closer to the Draeger or Westfalia type, but simpler in construction. Anhydrous sodium hydroxide in granules is used, but in largely increased amounts. The efficiency and endurance of the absorber are thus increased, and owing to the greater bulk of the alkali the heat is so distributed that the tendency to the development of an excessive temperature is considerably reduced.

GENERAL REQUIREMENTS OF BREATHING APPARATUS.

In order to be safe and efficient, breathing apparatus, whatever its type or the details of its construction, must comply with the following requirements:

1. An oxygen supply adequate alike to conditions of rest and violent exertion, and capable of being adjusted to last as long as possible, in case the wearer should happen to be imprisoned in bad air by a fall of rock or other cause.

2. Such efficient absorption of the carbon dioxide exhaled that the wearer, even during vigorous exertion and hard breathing, is not compelled to reinhale enough carbon dioxide to appreciably interfere with his capacity for exertion. One per cent should be the maximum, and less than half of one per cent the aim. The absorber should be able to take up an amount of carbon dioxide corresponding approximately to the total oxygen supply carried.

3. Freedom from mechanical obstruction in the apparatus, so that the wearer may inspire and expire even during the most violent breathing without noticeable impediment; no negative pressure at any time, as poisonous gases are liable to be sucked in; and a positive pressure at the mouthpiece of not more than 5 centimeters (2 inches) water gage even during the most forcible expiration.

4. Arrangements to obviate the danger of the breathing bag or bellows being breathed or squeezed empty when the wearer is crawling in a low passage, as he is then unable to inflate his lungs and may throw off the apparatus.

5. Tightness of the apparatus so that not even the smallest quantity of the poisonous gases by which the wearer may be surrounded can be drawn into the apparatus and so reach his lungs, the apparatus to

be as nearly accident proof and "fool proof" in this respect as possible.

6. The avoidance of an excessively high temperature—as produced by some of the absorbers now in use—and efficient heat radiation.

7. Simplicity of construction and such arrangements as will effectually protect the vital parts from breakage by striking against walls or roof or from the wearer's happening to fall.

OXYGEN REQUIREMENTS OF THE BODY DURING REST AND WORK.

One of the principal defects of mine rescue apparatus, as usually arranged, is that the oxygen supply is set at a fixed amount per minute and that this amount, although more than sufficient to cover the requirements of the wearer while resting, is quite insufficient to allow him to make vigorous physical exertion. The rate at which a man consumes oxygen varies. When sitting perfectly still he may consume less than 300 c. c. per minute; when walking at even a slow pace, from 800 to 1,200 c. c. per minute, while under moderate exertion a man of ordinary size and physical strength easily requires 2,000 c. c. per minute. Under vigorous exertion the consumption may rise for a time to 3,000 c. c. per minute. During short periods of extreme physical exertion even this amount may be considerably exceeded.

It is essential to distinguish between the volume of air that a man breathes per minute and the oxygen consumption. When he is at rest and breathing 12 to 18 times a minute with a tidal volume—that is, the amount inhaled and exhaled at each breath—of 400 to 700 c. c., the total amount of air breathed is only 5 to 13 liters per minute. On the other hand, during exercise a respiration of 1,500 or 2,000 c. c. 30 times a minute is not unusual—a total volume of 45 to 60 liters of air per minute. During short periods of extreme exertion and violent breathing a well-developed man may breathe 40 times per minute with a tidal volume of 2,500 c. c., or a total of 100 liters a minute. The amount of oxygen absorbed, both during rest and during work, is roughly about 4 per cent of the total tidal air per minute. As ordinary air contains about 21 per cent of oxygen, in ordinary conditions only about one-fifth of the oxygen inhaled is absorbed.

Oxygen is often spoken of as a food. In one sense this is correct, but the demand for oxygen differs from the demand for food in the fact that the supply of oxygen must be continuous. A man may go without eating for several days, and still be able to do considerable work. After being properly fed he may be none the worse for his experience. Conditions as regards the oxygen supply are far more peremptory. The amount that the body uses in any one minute it needs and must have within that minute, or at latest during the next succeeding minute. Even a slight deficiency in oxygen impairs intelligence and judgment and produces almost immediately a condition of intoxication or delirium, rendering the subject incapable of intelligent action and paralyzing the muscles so that he can not stand or walk. If this deficiency is continued for even a few minutes serious and often permanent injury to the nervous system or even death results.

The consumption of oxygen by the body is also sometimes compared to that of a fire. The analogy can not, however, be carried very far. If the oxygen supplied to a flame such, for instance, as that of a candle is increased either by a draft of air or by supplying pure oxygen instead of ordinary air, combustion proceeds at a greatly accelerated rate. This is not true, however, of the lungs, for a man breathing pure oxygen, or air enriched with oxygen, consumes no more than if breathing ordinary air. The amount that the body demands is determined wholly or almost wholly by the amount of physical exertion it is making, and varies within wide limits, corresponding to the widely varying amount of physical work involved in rest and in violent activity. A candle is extinguished when the oxygen in the surrounding atmosphere falls below 16 or 17 per cent. The blood of a normal man or animal at sea level is unable to absorb oxygen fully when the proportion in the atmosphere that he is breathing falls below about 13 per cent, and unconsciousness occurs at 9 or 10 per cent. Burning and breathing differ also in the fact that burning depends mainly on the percentage of available oxygen in relation to the other gases present, whereas the lungs depend almost solely upon the partial pressure of oxygen regardless of the other nontoxic gases present. Thus a candle will burn at an altitude where a man or animal brought directly from sea level would die. On the other hand a man can live in a denser atmosphere vitiated considerably beyond the point at which a flame is extinguished.

OXYGEN FEED PROVIDED BY PRINCIPAL TYPES NOW IN USE INSUFFICIENT.

These considerations have not heretofore been adequately taken into account. The manufacturers of one of the principal forms of rescue apparatus direct that the feed valve be adjusted to supply 1,800 c. c. per minute; the directions for another type state that 2,000 c. c. per minute should be used; and for a third type 2,200 c. c. is specified. In some mines it is the practice to set the oxygen flow at even smaller amounts, on the ground that even the lowest of the flows mentioned results in waste of oxygen. One mine foreman has made it a practice to set the oxygen supply at 800 to 1,000 c. c. per minute. It is clear that all makers of such apparatus and practically all of the men who have used them have counted on a small oxygen supply, for the regulations everywhere adopted direct that the wearer both in preliminary tests and in practical mine-rescue work shall walk slowly and shall stop to rest for a few minutes at least every 300 feet. Furthermore, it is not an unusual experience for the wearer of a breathing device, after an exertion in which his consumption of oxygen has exceeded the supply, to have to stop and wait for a sufficient amount of oxygen to reaccumulate in the breathing bag.

An idea of the amount of oxygen that a man of average weight consumes at rest and during various degrees of physical exertion up to the very moderate limit of walking at 5 miles an hour can be obtained from Table 1. The data in this table are from "Physiological Observations on Pikes Peak," by Douglas, Haldane, Henderson, and Schneider.[a] The observations were made by and on Douglas at sea level by means of the bag method devised by him.[b] The subject weighed 140 pounds stripped. The measurements are calculated to 0° C. and 760 mm. of mercury.

TABLE 1.—*Respiratory exchange of man under various degrees of exertion.*

Amount of exertion.	Number of breaths per minute.	Average volume of each breath.	Air breathed per minute	Oxygen consumed per minute.	CO_2 given off per minute.	Respiratory quotient $\left(\frac{CO_2}{O_2}\right)$
		Liters.	*Liters.*	*Liters.*	*Liters.*	
Resting in bed	16.8	0.457	7.7	0.237	0.197	0.829
Standing at rest	17.1	.612	10.4	.328	.264	.804
Walking 2 miles an hour	14.7	1.271	18.6	.780	.662	.849
Walking 3 miles an hour	16.2	1.530	24.8	1.065	.922	.866
Walking 4 miles an hour	18.2	2.060	37.3	1.595	1.398	.876
Walking 4½ miles an hour	18.5	2.524	46.5	2.005	1.788	.891
Walking 5 miles an hour	19.5	3.145	60.9	2.543	2.386	.938

It is here seen that the oxygen consumption of a man when resting in bed is only 237 c. c. per minute, whereas when the man is walking 5 miles an hour (carrying no load) it is over 2,500 c. c. per minute. As these volumes are calculated at 0° C., they would have to be increased by about 7 per cent for the ordinary temperature (20° C.) at which the oxygen flow of rescue apparatus is usually determined. The volume of each breath is seen to reach a maximum of more than 3 liters and the air breathed per minute a maximum of 60.9 liters, while the variations in the number of breaths per minute are insignificant, or even inverse. In strong men as a rule it is only during vigorous exertion, when the amplitude of breathing approaches its

[a] Douglas, C. G., Haldane, J. S., Henderson, Y., and Schneider, E. C., Psysiological observations on Pikes Peak: Phil. Trans. Roy. Soc. London, vol. 203, 1913, p. 35.

[b] Douglas, C. G., A method for determining the total respiratory exchange in man: Jour. Physiology, 1911, vol. 42, p. xvii.

limit, that a further compensation is effected by marked increase of rate; whereas in weak and shallow breathers the rate is accelerated by slight exertion.

In considering Table 1 it must also be kept in mind that a pace of 5 miles an hour for a man not carrying any considerable load is only moderate exertion. During vigorous exertion, as shown in Table 2, a well-developed man may consume for a short period even more than 3 liters of oxygen per minute. Under such conditions the CO_2 output and the volume of air breathed are correspondingly, or even in higher degree, augmented.

TABLE 2.—*Respiratory exchange of men undergoing vigorous exercise.*

Name of subject.	Weight.	Respirations per minute.	Volume per respiration.	Volume per minute.	Oxygen in exhaled air.	Carbon dioxide in exhaled air.	Volume of oxygen consumed per minute.	Carbon dioxide produced.	Respiratory quotient $\left(\frac{CO_2}{O_2}\right)$
	Pounds.		*Liters.*	*Liters.*	*Per cent.*	*Per cent.*	*Liters*	*Liters.*	
German, W. J.	147	28	2.67	75	17.60	3.30	2.50	2.47	0.980
Raudenbush, W. A.	197	27	2.29	62	16.71	4.14	2.11	2.56	.980
Jones, H. D.	185	33	2.33	77	16.98	4.10	3.04	3.15	1.037
Deike, G. H.	150	27	2.51	68	16.24	4.98	3.19	3.38	1.060

Table 2 shows the results of experiments conducted by the junior author of this report. The subjects were wearing apparatus weighing 35 to 40 pounds, with the mouthpiece disconnected from the apparatus and connected to a three-way cock leading either to the outside air or to a Douglas bag. The subjects thus inhaled outside air through a valve and exhaled into the outside air again until the cock was turned so that they expired into the bag. The exercise consisted in running back and forth over a measured stretch at a pace of 5 miles per hour for 10 minutes, and then running up and down a flight of stairs 14 feet 8 inches in elevation 10 or 12 times and until exhausted. During the stair-climbing period the exhaled air was caught in the bag, to be later measured (at 60° F. and 760 mm. of mercury) and analyzed. The extent of the exertion is indicated by the high respiratory quotients, indicating an excessive elimination of carbon dioxide in relation to the amount of oxygen absorbed. The ordinary respiratory quotient for a man at rest or during moderate exercise is 0.75 to 0.90. In the combustion of the foodstuffs within the body most of the oxygen combines with carbon to form CO_2, but some is consumed by other elements such as hydrogen and sulphur to form water, sulphuric acid, and other compounds.

In considering the respiratory exchange it is always necessary to take into account the character of the exertion and the size of the muscles used. Thus the subject may feel that he is making a great exertion and may soon become exhausted by pulling heavy chest weights with the comparatively small muscles of the arms, although he is consuming only a moderate amount of oxygen. On the other hand, there may be an equal or even a much larger consumption of oxygen without sense of effort or fatigue during rapid but easy walking, and even more during the ascent of a flight of stairs at an ordinary rate, because the large muscles of the legs are brought into action.

THE EFFECTS OF INSUFFICIENT OXYGEN.

The insidious effects of breathing air deficient in oxygen can not be overemphasized. The symptoms are in practically all respects identical with those of breathing carbon monoxide (a constituent of afterdamp), and in some respects resemble those of alcoholic intoxication. The peculiar danger of breathing such air lies in the fact that discretion and judgment are quickly impaired. Moreover, in many individuals, perhaps in most men, the breathing is at first so little affected that the man remains unwarned of his danger until his legs give way and he falls helpless.

A man who has been thus overcome does not usually recover completely and immediately on being brought into fresh air, because during the period of oxygen deprivation various incomplete combustion products accumulate in the blood, and the delicate cells of the nervous system are injured. For instance, in severe cases of carbon monoxide poisoning, the effects of which are largely due to lack of oxygen, the victim, after being rescued from the deadly atmosphere, often remains unconscious for several days and then dies. With cases in which the deprivation has been only brief the period of recovery frequently involves marked disturbances of breathing (intermittent or Cheyne-Stokes rhythm), nausea, and vomiting, and a throbbing headache that continues to increase in intensity for many hours. These sequelæ may be greatly diminished by administering immediately nearly pure oxygen. Later, after an hour, or even less, such treatment is ineffective.

EXPERIMENTS DEMONSTRATING THE EFFECTS OF INSUFFICIENT OXYGEN.

BREATHING INTO AND FROM 40-LITER BAG WHILE RESTING.

The subject was seated in a chair beside a table. The apparatus employed consisted of a bag containing 40 liters of air from which the subject inspired through a rubber tube, valve, and mouthpiece, and into which he again expired through another valve, and an alkali absorption cartridge. Thus the oxygen of the air in the bag was gradually consumed and the carbon dioxide exhaled was absorbed by the cartridge. The experiment lasted 18 minutes.

At no time was the subject's breathing noticeably increased either in rate or depth. As is usual in such experiments, there were no effects of any sort until the oxygen content in the bag had been reduced below 13 per cent. After about 12 minutes the subject's lips were distinctly blue and his hands trembling so that he was unable to hold anything in them. During the last three or four minutes he became much excited, waving his arms and trying to speak. Although on the verge of collapse and loss of consciousness, he did not wish to stop the experiment, failing to appreciate his own condition, in a manner closely similar to that frequently observed in men affected by insufficient oxygen or by carbon monoxide when wearing mine rescue apparatus. He experienced no discomfort at this time, but felt and acted like a man under the influence of alcohol. When the mouthpiece was pulled out of his mouth he drew a couple of breaths and seemed to lose consciousness for a few seconds. He was unable to stand or walk for some minutes thereafter and then had to be assisted at first. He reported that on the day following he felt as if he had been drugged, and in moving about each movement was accompanied by sharp pains in his head. This effect wore off entirely by the second day. Analyses of air taken from the bag two minutes before the end of the experiment showed 7.55 per cent of oxygen and 0.16 per cent of carbon dioxide. At the end of the experiment the oxygen content was 6.01 per cent and the carbon dioxide content 1.54 per cent.

BREATHING INTO AND FROM CLOSED TANK WHILE WORKING.

A young man was set to perform an experiment to determine the rate of oxygen consumption at various rates of work on a stationary bicycle. By means of a mouthpiece and tubing he breathed from and into a large gasometer through a can of soda lime, which absorbed the carbon dioxide exhaled. Instructions were that the gasometer should be filled with oxygen at the beginning of the experiment, but through a mistake it was filled with air. After a few minutes' vigorous exertion on the bicycle the oxygen percentage had been so much reduced that the subject, who had no suspicion that anything was going wrong, suddenly lost consciousness and fell off the bicycle, twitching and kicking as in a convulsion. In a few minutes, after breathing fresh air, he recovered consciousness and seemed none the worse except for a slight headache. He had no recollection of what had happened.

BREATHING INTO AND FROM CLOSED TANK WHILE RESTING.

Another man performing a similar experiment, but resting, had been warned not to push it too far. Feeling nothing wrong, however, he continued until his lips were blue and his hands twitching. When directed to discontinue he stated that he felt well. A few minutes later he fainted and was obliged to lie down for a couple of hours. During the first hour he exhibited marked respiratory disturbance (Cheyne-Stokes breathing) and intermittent periods of unconsciousness. Later he had a violent headache.

EFFECTS OF FAILING TO TURN ON THE OXYGEN.

A member of a rescue crew, upon starting into a mine to recover a comrade who had been overcome, failed to turn on the oxygen in the apparatus he was wearing and fell unconscious 20 feet inside the drift entrance. Upon removal to fresh air he immediately recovered, and after turning on the oxygen proceeded to assist in the recovery of his comrade.

A member of a crew engaged in a field-day exhibition failed to turn on the oxygen. After closing the apparatus and applying his nose clip he entered a smoke room and fell unconscious. After he had been removed to fresh air and his apparatus detached he remained in a stupor for three minutes, and upon recovery did not recall his experience.

A mine foreman closed his apparatus, applied the nose clip, and started for the training quarters without turning on the oxygen. After he had proceeded about 100 feet he fell unconscious. He had not enough warning of danger to induce him even to lift his hand to his nose to remove the clip so that he could inhale the outside air.

IMPORTANCE OF EFFICIENT CARBON DIOXIDE ABSORPTION.

Second only in importance to a sufficient supply of oxygen is an efficient arrangement for absorbing from the air in the apparatus the carbon dioxide that the wearer produces. One of the most important facts demonstrated by recent advances in physiology is that in normal men and animals, under ordinary conditions, the amount of breathing is principally regulated, not by the oxygen consumption, but by the carbon dioxide produced. The respiratory center in the nervous system, which controls the breathing, is in most men, as illustrated by the experiments in the preceding section, relatively insensible to deficiency of oxygen; but on the other hand it is acutely responsive to minute variations in carbon dioxide. When a man exercises he requires more oxygen for the working muscles than when he is at rest. At the same time more carbon dioxide is produced, and the effect of the increased quantity of this waste product, which is carried by the blood to the respiratory center, is to excite an accurately adjusted increase of breathing, so that the excess of carbon dioxide is thrown off and the needed amount of oxygen absorbed. Thus, as an eminent physiologist expressed it, "Carbon dioxide spreads its protecting wings over the oxygen supply of the body."

In a similar manner the breathing of air containing even a small amount of carbon dioxide immediately induces a corresponding increase in the amount of the breathing, in most cases affecting at first the depth rather than the rate of breathing. Such air also reduces the amount of muscular work that a man can do. A man sitting perfectly still may breathe an atmosphere containing amounts of carbon dioxide up to 3 per cent without dyspnœa (panting) noticeable to himself. If, however, the volume of his breathing is measured it is always found to be considerably increased.

On the other hand, a man trying to do work while breathing an atmosphere containing 3 per cent of carbon dioxide is handicapped to just this extent—that in addition to the panting induced by the exertion he must breathe harder because of the vitiation of the air. A man sitting perfectly still pants noticeably when breathing an atmosphere containing 3 or 4 per cent carbon dioxide. With proportions above 5 per cent about all that one can do is to breathe; any considerable and prolonged exertion is impossible.

Even when the subject is sitting perfectly still a content of 8 per cent carbon dioxide in the inspired air, if continued for a few minutes, induces not only violent breathing but in most subjects a splitting headache, confusion of mind, and an inability to see clearly. Although the immediate risk to life from excess of carbon dioxide is not as great as that from lack of oxygen—and the effects of the former wear off in as many minutes as those of the latter require hours—the immediate intoxication and weakening of judgment are almost equal in these two forms of asphyxia.

As has been previously stated, all of the present forms of apparatus involve complete rebreathing from a closed system. The carbon dioxide produced by the wearer is absorbed by alkali contained either in the breathing bag or bags, or in a metal box. For reasons already stated it appears improbable that any apparatus can ever be devised for use for more than a few minutes at a time with which the wearer will not do any rebreathing whatever. It is especially important, therefore, that the alkali should be so arranged as to absorb as completely as possible the carbon dioxide exhaled by the subject into the bags before he again inspires the air.

One of the commonest effects of wearing the present forms of breathing apparatus is a throbbing frontal headache, which in most cases quickly wears off if the apparatus is removed. This headache is usually assigned by the wearer to the tightness of the helmet over the temples, if a helmet was worn, or to other mechanical causes. As a matter of fact, in most instances the headache is an indication of a considerable degree of carbon dioxide intoxication. For proof of this point it is necessary only to compare such experiments as Nos. 5 and 7 in Table 5, in one of which a helmet was worn, whereas in the other a mouthpiece was used, but poor absorption of carbon dioxide occurred. When the amounts of carbon dioxide in the air breathed were equal, both subjects developed headaches of equal intensity, as nearly as could be judged.

The carbon dioxide content of the air in an apparatus ought not to rise above 1 per cent; and preferably should be kept below 0.5 per cent, not so much to insure the safety and comfort of the wearer as for his efficiency as a worker. Practical experience in the effects of breathing air high in carbon dioxide shows that the muscles of the chest seem to be under a great strain. The subject is often inclined to believe that the trouble, which he mistakenly interprets as inability to draw sufficient air into his lungs, is due to restricted passages in the circulating system of the apparatus. Of course, if there is such a mechanical obstruction, in addition to a considerable percentage of carbon dioxide in the breathing bag, the effects on the wearer are peculiarly distressing.

EXPERIMENTS ON EFFECT OF BREATHING CARBON DIOXIDE.

The following experiments illustrate the distressing effects of breathing air containing a considerable percentage of carbon dioxide, and the marked effects of even small percentages.

BREATHING INTO AND FROM 40-LITER BAG WHILE RESTING.

The subject was seated in a chair and breathed into and out of a bag containing 40 liters of air. At the end of one minute the breathing was markedly deeper than at the beginning, but not appreciably quicker. After two minutes he was breathing as deeply as possible, and more rapidly. After three and one-half minutes the subject was breathing 40 times a minute, he was experiencing considerable distress, his face was flushed, and he perspired considerably. The experiment was then stopped. Analysis showed that the air in the bag at the end of the experiment contained 17.49 per cent oxygen and 3.81 per cent of carbon dioxide. The effects in this case were wholly or almost wholly due to the accumulation of carbon dioxide, as decreased oxygen produces no marked immediate effects until the proportion falls below 13 per cent. These results should be compared with results of experiments on low-oxygen atmospheres on pages 28 to 30. The adequacy of the oxygen supply was also indicated by the fact that the lips were throughout a bright-red color.

BREATHING FROM 65-LITER BAG INTO OPEN AIR.

A Douglas bag of 65-liter capacity was filled with 90 strokes of an air pump. The subject sat still for 10 minutes. He then breathed through a mouthpiece with the inspiratory valve connected to the bag and the expiratory valve opening to the outside air. The bag was thus emptied in 5 minutes. The experiment was then repeated with the bag filled with air containing 2.2 per cent carbon dioxide—that is, 88 strokes of the pump with fresh air and 2 strokes with carbon dioxide gas drawn from a tank. The contents of the bag were then thoroughly mixed by kneading. The bag thus filled was breathed empty in 2.5 minutes.

A man walking at a rate of 3 miles an hour emptied the bag in 2 minutes and 22 seconds when it contained air, and in 1 minute and 30 seconds when it contained 4.4 per cent carbon dioxide.

CIRCULATION OF AIR IN THE DRAEGER AND WESTFALIA APPARATUS.

In the Draeger and Westfalia types of apparatus the expired air is driven or drawn through the absorber and into the inspiratory bag by an injector through which the oxygen enters the circulation system. As ordinarily adjusted on the Draeger apparatus the volume of this automatic circulation may fall as low as 50 liters per minute, and in some apparatus, even below 40 liters. Fifty liters per minute is, indeed, more than a man will breathe when at rest or making an exertion equivalent to walking 2 miles an hour, but it is less than the amount that he may breathe during vigorous exertion. The tidal movements of respiration may then amount to 60 or 70 liters a minute, or even more. So long as the automatic ventilation of the apparatus exceeds the volume of the wearer's breathing the inspiratory bag is kept full and the expiratory bag is emptied. But when the rate of breathing exceeds the automatic circulation the expiratory bag is overfilled and the inspiratory bag is drawn flat at each breath. Thus conditions are produced under which the subject can not get the air volume that his lungs demand. This produces a sensation so peculiarly terrifying that few men are able to resist the temptation to tear off the apparatus, even in the midst of deadly gases.

Natural circulation—that is, movement of air produced by the subject's breathing, as in the Fleuss apparatus—is to be preferred to automatic circulation induced by an injector. One particular advantage of natural circulation is that if the wearer happens to become imprisoned in "bad air" he can make his oxygen supply last for many hours by turning off the fixed feed valve on the oxygen tank and using the by-pass at intervals to supply the relatively small oxygen consumption during rest. Otherwise the supply would run out at the end of about two hours and the man would lose his life. With apparatus of the automatic circulation type, such conservation of oxygen is impossible, for turning off the oxygen feed stops the absorption of carbon dioxide in the Westfalia and makes breathing labored in the Draeger.

If automatic circulation is to be used it should insure a volume of air of not less than 80 liters a minute. This is obtainable by an increase in the oxygen feed and is important in connection also with the absorption of carbon dioxide. The greater the flow of oxygen through the feed valve and injector the more rapid the circulation. This prevents the accumulation of gas in the expiratory bag and the dangerous depletion of the inspiratory bag during heavy breathing by the wearer. The absorption of carbon dioxide is also thus increased. Insufficient absorption of carbon dioxide tends to set up a "vicious circle" in both the Westfalia and the Draeger apparatus. A detail in each of those types of apparatus indicates that the circulation of neither type is as rapid as is necessary in times of stress. Thus, in the Draeger 1907 model there is a small opening between the inspiratory and expiratory bags, whereas the Draeger 1910 model and the Westfalia have no valve in the tube to the expiratory bag. During the deep and rapid breathing incident to vigorous bodily exertion, when the volume of air breathed by the subject exceeds the automatic circulation in the Draeger, the excess, instead of being pumped around through the absorbing cartridge, is in part short-circuited from the expiratory bag to the inspiratory bag through this opening. Under similar conditions in the Westfalia the wearer draws back a part of each breath from the expiratory bag. The result is that the wearer rebreathes expired air from which the carbon dioxide has not been absorbed. This condition stimulates him to even more violent breathing, and in consequence more expired air passes through the opening or back through the tube and is rebreathed, until the utmost limit of dyspnoea is reached, and he collapses.

There should never be any rebreathing of air that has not passed through the absorber; yet, in these forms of apparatus, if it were not for the arrangements mentioned, or some similar device, the inspiratory bag would be liable to be breathed flat, as has occurred frequently in tests by the authors. The wearer would then be unable to fill his lungs, and would be tempted to tear off the apparatus. In one of the latest models of the Draeger (model 1911–12), which has both inspiratory and expiratory valves, but no short-circuiting opening between the bags, the wearer is exposed to this supreme danger. (See results of experiments Nos. 1, 4, 5, and 6, Table 5, and Nos. 1 to 4, inclusive, Table 6.)

EFFECT OF HELMET IN PRODUCING CARBON DIOXIDE INTOXICATION.

No subject in regard to rescue apparatus has been more debated than the use of the helmet. Many practical mining men insist that the helmet is advantageous in that it allows the wearer to speak more distinctly and to breathe through his nose, a more natural method of breathing than with the mouthpiece and nose clip. Although the mouthpiece in its present form is open to much just criticism, the use of a helmet of such a type as that provided with the Draeger apparatus and sometimes also with the Westfalia should be absolutely condemned. It necessitates the wearer's breathing into a "dead space" greater than the volume of an ordinary deep breath. The air that the wearer expires into this space he is obliged, in great part, to reinspire from it. The vitiation is increased by physical exertion.

In order to measure this "dead space," a helmet was filled with water, and the face placed in position, the excess of water being allowed to escape. Then the water was poured off into a measuring vessel. The measurements on several men of various shapes of face gave an average "dead space" of about 2,400 c. c. Analyses indicate that, owing to the fact that the wearer of a helmet breathes into and from this space instead of from the bag, the air in the mask usually contains 2 to 3 per cent more of carbon dioxide than that in the inspiratory bag. During moderate exercise, such as walking 2 miles an hour, the accumulation of carbon dioxide in the mask is often not enough to cause the wearer serious inconvenience, although, as pointed out above, the headache that usually results from wearing a helmet is mainly due to mild carbon dioxide intoxication from this rebreathing of the expired air rather than to the tightness of the helmet around the temples. But, as the authors' experiments have shown conclusively, vigorous exercise while wearing the helmet causes collapse, even when the remainder of the apparatus is so efficient that a man wearing it with a mouthpiece instead of a helmet comes through the test with ease.

The authors are aware that their condemnation of the helmet will meet with skepticism on the part of some practical mining men. However, if any skeptic will put on the apparatus with the helmet, and attempt to walk at the rate of 5 miles an hour for 15 or 20 minutes, his skepticism will vanish. As the result of tests in England by Dr. J. S. Haldane, similar to those made by the authors, the London fire department has discarded its entire equipment of helmets. The Bureau of Mines as far back as 1912 discarded the helmets entirely. It was found that in practice maneuvers and in actual mine rescue work, in which one man or a number of men wore helmets and others were equipped with mouth-breathing apparatus, the former usually suffered from a severe headache and much exhaustion, whereas the latter experienced relatively little discomfort.

The effects of an excessive accumulation of carbon dioxide in the dead space of the helmet are illustrated by the following observations.

OBSERVATIONS WITH DRAEGER HELMET, MODEL OF 1907.

OXYGEN SUPPLY 2 LITERS PER MINUTE.

Some experiments were conducted with the Draeger helmet in which the rate of oxygen supply was 2 liters a minute and the circulation 35 liters a minute. After walking up and down a large room as rapidly as possible for five minutes the subject was breathing violently and was unable to see clearly. He was also beginning to reel slightly as he walked. The experiment was then discontinued. The subject was perspiring vigorously. His breathing abated in a few minutes, but he had a severe headache for half an hour. The acute but brief character of a headache induced by carbon dioxide contrasts strikingly with the slow development but long duration of a headache caused by lack of oxygen.

OXYGEN SUPPLY 3 LITERS PER MINUTE.

On the following day the oxygen supply of the apparatus was increased to 3 liters a minute, as it was thought that this might improve the air circulation and keep down the carbon dioxide accumulation. In the first subject on whom the apparatus was then tried there was marked respiratory distress after two minutes' walking at 4 miles an hour. In three minutes the subject was stumbling about, and, feeling himself about to fall, stopped the experiment. As this subject may have been unusually sensitive to carbon dioxide, the apparatus was removed and placed on another person. He walked at a rate of 4 miles an hour back and forth over a measured stretch on a level pavement out of doors. In two minutes he was panting severely and was becoming unsteady, but he persevered with the experiment and kept walking for four minutes, when he appeared to be about to fall. On the removal of the helmet he was barely conscious. He thought that he had been walking for an hour. After about one and one-half minutes he was again coherent, though still breathing deeply. There was no blueness of the face and the symptoms were quite clearly due to intoxication with carbon dioxide. He reported that everything had looked dark toward the end of the experiment, and that he had felt as if he were taking an anesthetic. As the subject was probably breathing not less than 70 liters of air a minute, and the automatic circulation of the apparatus was scarcely half of this amount, a large percentage of the expired air must have passed from the expiratory to the inspiratory bag through the opening between them, and must thus have been rebreathed without having been through the absorber. In addition to this the subject was breathing into and rebreathing from the dead space of the helmet.

Objection may be made to these experiments on the ground that it is not necessary, or even possible, for a man in actual mine rescue work to walk at a pace of 4 or 5 miles an hour. He may, however, have to climb ladders and carry or drag another man; and the consumption of oxygen, elimination of carbon dioxide, volume of breathing, and amount of heat produced by such severe exertions considerably exceed those of a man walking rapidly on level ground.

THE DANGER OF LEAKAGE WITH THE HELMET.

The defects of the helmet above shown are serious, but the greatest objection to its use is the danger of leakage. Numerous observations made during the training of rescue crews in the presence of irritating fumes, for instance, sulphur dioxide and formaldehyde, in the smoke room have demonstrated the liability of the helmets to leakage. In actual rescue operations the greatest of all dangers is that through cracks, crevices, breaks, or loose joints in some parts of the apparatus the deadly gases by which the wearer is surrounded will find entrance. Records collected by the Bureau of Mines of fatal accidents among men wearing apparatus indicate that most of the deaths have probably been due to a leakage of carbon monoxide into the helmet.

In an atmosphere containing several per cent of carbon monoxide, such as may be caused by an explosion of coal dust in a mine, or in the smoke of a burning building, the slightest leakage into the apparatus is a danger in comparison with which other details, such as oxygen flow and carbon dioxide absorption, are relatively unimportant. In the experience of the rescue crews of the Bureau of Mines it has repeatedly happened that after a man has been overcome and has lost his life, or has been rescued and revived with difficulty, examination of the apparatus which he had been wearing has shown that it was in good working order, except that it leaked.

Users of apparatus often fail to realize how large a volume of gas will pass in even a few minutes through an almost imperceptible crack, through which water would scarcely drip, under a difference of pressure that the wearer of the apparatus fails to notice.

The carbon monoxide that finds its way into an apparatus is breathed and rebreathed from the small air space, and the greater part is quickly absorbed in the wearer's lungs. The haemoglobin or red matter of the blood is thus rendered in proportion incapable of transporting oxygen. The amount of carbon monoxide required to cause collapse in man is only 400 to 600 c. c., and a much smaller amount is sufficient to render him incapable of exertion and to deprive him of clear judgment. In effect, it acts like acute deprivation of oxygen.

Experienced men claim that the helmet can be made tight. This is possible, but certainty, not possibility, is needed in such a vital matter. Owing to the construction of the helmet minute cracks, which easily escape detection, frequently develop where the various materials are joined. The chief points of leakage are, however, between the rubber ring or cushion which is inflated to fill the space between the edges of the helmet and the face. The human face is a peculiarly difficult object upon which to make an accurate fit. The pneumatic ring of the helmet is necessarily made of soft and elastic rubber. In the American climate, and particularly in the West, this rubber tube rapidly deteriorates, grows stiff, and when fully inflated breaks. Even when new and inflated so tightly as to make deep grooves in the skin of the face it often happens that instead of the tube fitting smoothly around the chin it folds into one or more grooves that leave small irregular openings. Considerable leakage occurs also through the wearer's hair unless it is plastered down with water, soap, or vaseline.

In many cases in which the wearer believed the helmet was on airtight, the authors have found that if the wearer expired deeply and the breathing tubes were then clamped he could in the course of half a minute draw his lungs quite full of air—3 liters or more. If he then immersed his head and helmet in a tub of water and exhaled, air bubbled up from under the rubber tube, through his hair, around his cheeks and chin, and frequently also from undetected cracks in the helmet.

The first experience of one of the authors with breathing apparatus was in an examination of a helmet in which a city fireman had lost his life in a sewer into which illuminating gas was escaping. This helmet leaked so easily that when the connections from the breathing tubes were closed the wearer could draw almost enough air through the cracks to satisfy his needs when resting. Inspection of the helmets kept to-day at various mines in America awaiting a mine accident indicates that if ever used they are more likely to contribute to the loss of life than to decrease it.

OXYGEN SUPPLY AND CARBON DIOXIDE ABSORPTION IN TESTS OF BREATHING APPARATUS.

The usual method of training for mine rescue work in the past has been to put the wearer of the apparatus into a smoke chamber with a floor littered with blocks, beams, and other débris, with barrels to crawl through and ladders to climb, and in semidarkness. The room frequently is hot and uncomfortable, so that the subject gains an impression that he is making greater exertions than he actually is. By this statement it is not intended in the least to minimize the importance of training in a smoke chamber. It is in fact vitally essential that all men who are to wear rescue apparatus in mine work should have such training, as it accustoms the wearer of the apparatus to conditions closely resembling those underground, although even in the smoke chamber it is not possible to reproduce the mental strain, anxiety, and fear sometimes manifested in mine-recovery work. Thus some men who behave well in the smoke chamber become excited too easily in actual work, and this manifests itself in extremely deep and rapid breathing, which the ordinary type of apparatus is unable to support.

The schedule for training work in a smoke room is as follows:

SCHEDULE OF TRAINING WORK WITH RESCUE APPARATUS IN SMOKE ROOM.

1. Walk 20 laps in room at rate of 3 miles per hour.
2. Carry six props over overcast or an obstruction and wedge up under a collar.
3. Carry brattice cloth over overcast or an obstruction and hang up at a place designated.
4. Carry a dummy over overcast or an obstruction and leave at place found.
5. Carry 150 bricks, in lots of 10, in gunny-sack over overcast or an obstruction and build a dry wall.
6. Take down props and brattice cloth and return to place where originally found.
7. Crawl through tunnel four times. This tunnel may be constructed of boards which can be found at almost any mine. Dimensions to be: 19 inches high, 17 inches wide, and 16 feet long.
8. Lay and connect four pieces of 2-inch pipe.
9. Pull weight machine 50 times, or lift sand bag 25 times.
10. Disconnect pipe and return to place where originally found.
11. Walk at the rate of 3 miles per hour, resting at end of each minute, until two hours are completed.

In addition to tests and training in a smoke room it is essential that there should be equally thorough tests in the open air, where vigorous exertion can be carried out, as a means of determining the physical capacity of the men and the extent to which apparatus can be depended upon under maximal demands.

For these tests in the open air it has been found convenient to use what will be here spoken of as the 2, 3, 4, and 5 mile an hour paces. A stretch of 88 feet is laid off on level ground, and the wearer of the apparatus is directed to cover this distance twice a minute, or three, four, or five times a minute, according as the 2, 3, 4, or 5 mile an hour pace is to be maintained. Two miles an hour is a slow walk; 4 miles an hour a fast walk, and 5 miles an hour for most men is a "jog trot." Making the turns at each end of the 88-foot stretch adds an exertion involving a greater expenditure of energy and consumption of oxygen than would be necessary for a long straightaway course. The weight of the apparatus that the subject carries is 35 or 40 pounds, or about 20 to 25 per cent of his body weight. Carrying this increases both the energy expenditure and oxygen consumption. Zuntz and Schumberg[a] have shown that the percentage increase in energy expenditure caused by carrying such a load is less than the proportion of the load to the weight of the body. Thus, carrying a load equal to 25 per cent of the body weight increases the oxygen consumption by 15 or 20 per cent of the amount required in walking at a corresponding pace without a load. Hence, for a vigorous man wearing an apparatus weighing 30 to 40 pounds and performing the "5-mile-an-hour" test for 15 or 20 minutes at a time, the exertion involved as measured in cubic centimeters of oxygen used still falls considerably short of the maximal exertion of which he would be capable for a few minutes in an effort to save his own life and escape from a mine. In the mine, however, he risks his life in making such an effort, if the oxygen supply is inadequate.

In Tables 3 to 8, inclusive, are given a few selected and typical results from a large number of tests carried out along these lines, chiefly at the Bureau of Mines experiment station in Pittsburgh. By means of such tests it becomes apparent very quickly whether or not an apparatus adjusted to a certain rate of oxygen supply is capable of sustaining vigorous or only moderate exertion. If the oxygen supply or the carbon dioxide absorption is insufficient for the wearer's needs he exhibits almost immediately marked distress and may even collapse, but recovers within a few minutes if the apparatus is removed.

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[a] Zuntz, N., and Schumburg, —; Studien zu einer Physiologie des Marsches, Berlin, 1901, 361 pp.

TABLE 3.—*Results of analyses of air from inspiratory bag of breathing apparatus worn in smoke-chamber tests.*

[Rate of oxygen supply, 1,800 to 2,000 c. c. per minute.]

Wearer.	Time of wearing apparatus.	Oxygen and carbon dioxide in air from inspiratory bag.					
		Draeger mouth-breathing apparatus.		Fleuss apparatus.		Westfalia apparatus.	
		O_2	CO_2	O_2	CO_2	O_2	CO_2
	Minutes.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Denny, E. H.	15	57.80	0.12	54.50	1.90	70.00	0.00
	45	55.89	.16	87.50	1.70	79.60	.70
	75	56.41	.25	76.60	1.00	86.00	.40
	120	46.51	.11	....	....	24.30	5.40
McElroy, G. E.	15	39.77	.16	77.80	.20	57.80	.20
	45	37.05	.28	78.10	.00	69.20	.00
	75	68.84	.52	68.90	.30	69.20	.60
	120	54.51	3.81	83.80	1.80	71.10	5.80
Sanford, S.	15	43.06	.42	46.30	1.00	68.80	1.20
	45	51.05	1.35	80.50	.30	85.60	.10
	75	57.95	.19	54.50	.60	67.10	1.40
	120	65.13	.79	76.40	1.20	68.70	5.00
Freeman, W.	15	36.90	.70	34.10	.10	30.00	.60
	45	47.70	1.50	51.5	.20	32.10	3.20
	75	68.50	.30	77.00	.40	55.50	3.80
	120	63.80	3.80	77.20	.40	58.80	4.00
Leopold, M. F.	15	42.90	.00	67.40	1.20	69.30	.40
	45	42.80	.20	70.90	2.10	86.10	.50
	75	50.80	.10	72.20	2.10	77.30	.90
	120	49.60	.10	77.40	2.00	....	....

In nearly every case shown in Table 3 in which the carbon dioxide content in the apparatus rose above 3 per cent the subject had a headache, and when it rose to 5 per cent or more he exhibited marked distress of breathing and soon became exhausted. There are, however, wide variations in susceptibility to carbon dioxide intoxication. In most of the experiments, the breathing bags remained full during the first half of the test, indicating that the oxygen supply and circulation were adequate. In the other cases, and in the latter part of most of the experiments, the bag was partly deflated and the wearer's activity was correspondingly impeded.

TABLE 4.—*Results of tests in which men wearing breathing apparatus walked at a rate of 2 miles per hour in open air.*

[Covering stretch of 88 feet and return each minute, oxygen supply 1.80 to 3.06 liters per minute.]

Test No.	Wearer.	Apparatus.	Oxygen supply per minute.	Air in circulation per minute.	Duration of test.	Air samples.				Remarks.
						Time taken, minutes after start.	O_2 content.	CO_2 content.	Source of sample.	
			Liters.	*Liters.*	*Minutes.*		*Per cent.*	*Per cent.*		
1	Denny, E. H.	Draeger, model 1911 (mouth breathing).	1.84	57	21	10	71.51	0.13	Inspiratory bag	Bags well filled; wearer comfortable; pulse did not rise above 74 per minute, nor respiration above 20.
						12	73.84	.10	.....do	
						17	77.86	.23	.....do	
						19	77.83	.10	.....do	
2	.....do	Draeger, model 1910 (cartridge).	2.0		120	15	59.36	.10	.....do	Exhalation bag flat, and inhalation bag half distended during test; cartridge heated from bottom to top; bottom gradually cooling, top increasing in heat.
						30	73.97	.10	.....do	
						45	80.16	.10	.....do	
						60	82.91	.10	.....do	
						75	74.27	.10	.....do	
						90	67.32	.10	.....do	
						105	73.90	.10	.....do	
						120	61.27	.59	.....do	
3	Deike, G. H.	Draeger, model 1911 (mouth breathing).	3.00	75	19	10	56.33	.34	.....do	No complaint of excess oxygen.
						12	58.16	.10	.....do	
						17	55.51	.38	.....do	
						19	55.76	.06	.....do	
4	Denny, E. H.	Draeger, model 1911 (helmet).	2.00	70	17	10	31.69	.47	.....do	High carbon dioxide content in helmet; pulse 112; respiration very deep.
						12	33.15	2.36	Helmet	
						15	40.38	.29	Inspiratory bag	
5	McElroy, G. E.	.....do	2.86	72	12	8	71.09	.10	.....do	High carbon dioxide content in helmet.
						11	68.63	2.43	Helmet	
6	.....do	Fleuss [a]	1.85		120	15	88.58	.10	Inspiratory bag	Bag shaken frequently, kept one-half to three-fourths distended at all times. Bag warm in 30 minutes, hot at finish.
						30	94.45	1.19	.....do	
						45	92.96	1.30	.....do	
						60	96.09	.90	.....do	
						75	91.87	1.99	.....do	
						90	97.49	.78	.....do	
						105	96.01	.80	.....do	
						120	97.08	.98	.....do	
7	.....do	.....do	1.80		18	10	85.50	.37	.....do	Wearer worked blow-off, but did not shake bag.
						16	91.20	1.05	.....do	
8	.....do	.....do	3.06		17	10	86.90	.56	.....do	Wearer had to work blow-off 10 times.
						15	90.26	1.00	.....do	

9	.....do	Westfalia, model 1913, No. 11 (cartridge).	2.40	....	120	15	88.96	.10	.....do	Front bag kept well distended, back bag flat; cartridge uniformly hot, increasingly hot at top, and cooling at bottom as test progressed.
						30	94.82	.10	.....do	
						45	95.05	.40	.....do	
						60	95.59	.19	.....do	
						75	95.95	.43	.....do	
						90	96.00	.10	.....do	
						105	96.89	.79	.....do	
						120	96.38	.42	.....do	
10	Deike, G. H.	.....do	2.20	60	25	12	82.15	.74	.....do	Pulse at beginning of test 77, at end 78; respiration 18, at end 20.
						24	89.65	.66	.....do	

[a] Stick NaOH, 4 pounds, used.

Table 5.—*Results of tests in which men wearing breathing apparatus walked at a rate of 4 miles per hour in open air.*

[Covering level stretch of 88 feet and return twice each minute, with oxygen supply of 1.00 to 3.06 liters.]

Test No.	Wearer.	Apparatus.	Oxygen supply per minute.	Air in circulation per minute.	Duration of test.	Air samples. Time taken, minutes after start.	Air samples. O_2 content.	Air samples. CO_2 content.	Air samples. Source of sample.	Remarks.
			Liters.	*Liters.*	*Minutes.*		*Per cent.*	*Per cent.*		
1	McElroy, G. E	Draeger, model 1911 (mouth breathing).	1.84	57	12	7	13.01	0.34	Inspiratory bag...	Inspiratory bag flat, expiratory bag full; wearer could not get sufficient air; showed much distress and had to stop, trembling; pulse rose from 84 to 120; insufficient oxygen and circulation, high CO_2.
						10	9.94	1.21	.....do............	
						11	17.21	9.10	.....do............	
2	Denny, E. H..	.....do...............	2.92	72	23	8	44.62	0.15	.....do............	Both inspiratory and expiratory bags well filled; wearer felt well.
						20	39.22	3.64	.....do............	
3	Raudenbush, W. A.	.....do...............	1.00	12	2	2	12.53	3.64	.....do............	Had to stop for lack of air.
4	.....do.........	Draeger, model 1911 (helmet).	2.20	68	12	5	24.78	3.23	Helmet..........	Inspiratory bag flat; wearer could not get enough air, reeled, and had to be supported; dyspnœa mainly caused by carbon dioxide content in helmet.
						10	18.28	3.57	.....do............	
						12	19.01	3.20	.....do............	
5	Denny, E. H..	.....do...............	2.00	64	15	10	27.37	.80	Inspiratory bag...	Inspiratory bag flat; breathing heavily, caused by carbon dioxide content in helmet; headache.
						11	23.86	2.63	Helmet..........	
						12	33.48	.40	Inspiratory bag...	
						13	24.45	3.99	Helmet..........	
6	McElroy, G. E	.....do...............	2.86	72	21	10	39.21	.73	Inspiratory bag...	Inspiratory bag nearly flat at end of test; heavy breathing caused by carbon-dioxide content in helmet; pulse rose from 84 to 100; respiration rose from 20 to 32; aside from deep breathing wearer felt well.
						12	38.29	2.74	Helmet..........	
						16	42.21	.40	Inspiratory bag...	
						18	41.73	2.49	Helmet..........	
7	Freeman, W..	Draeger, model 1911 (mouth-breathing).[a]	3.06	([b])	23	3	51.30	3.60	Inspiratory bag...	Wearer had bad headache for an hour caused by carbon dioxide.
						21	54.79	3.01	.....do............	
8	Raudenbush, W. A.	Fleuss...............	1.00	....	5	5	9.33	1.38	.....do............	Bag flat; subject had to stop for lack of air; pale and sick from lack of oxygen; did not shake bag.
9	.....do.........	.....do...............	1.0	....	4	4	27.17	.20	.....do............	Shook bag; bag flat; could not get enough air, but felt all right.
10	McElroy, G. E.	.....do...............	1.81	....	18	10	83.70	1.60	.....do............	Wearer did not shake bag nor use by-pass; bag slightly deflated.
						16	79.80	2.65	.....do............	
11	German, W. J.	....	1.87	....	18	10	46.63	.53	.....do............	Wearer shook bag; by-pass not used; bag slightly deflated.
						16	57.49	.34	.....do............	
12	.....do.........	.....do...............	1.87	....	22	10	49.11	.43	.....do............	Wearer shook bag and worked by-pass 8 times.
						20	68.42	.31		

13	Deike, G. H.	....do	3.06	....	19	10 16	27.70 31.67	3.50 3.19	....do ....do	Wearer did not shake bag or use by-pass or blow-off; bag always full; feeling of oppression caused by high carbon dioxide content.
14	....do	....do	3.06	....	19	10 16	28.92 31.98	.39 .76	....do ....do	Wearer shook bag; noted distinct relief by so doing; did not use by-pass or blow-off.
15	....do	Westfalia	2.20	60	25	10 22	50.93 55.20	.83 .75	....do ....do	Bag fairly full; wearer felt well.

a Injector removed. b Natural circulation.

TABLE 6.—*Results of tests in which men wearing breathing apparatus walked at rate of 5 miles per hour in open air.*

[Covered level stretch of 88 feet, with turns, five times a minute at a dog trot; oxygen supply, 1.84 to 3.09 liters per minute.]

Test No.	Wearer.	Apparatus.	Oxygen supply per minute.	Air circulation per minute.	Duration of test.	Air samples. Time taken, minutes after start.	Air samples. Oxygen content.	Air samples. Carbon dioxide content.	Air samples. Source of sample.	Remarks.
			Liters.	*Liters.*	*Minutes.*		*Per cent.*	*Per cent.*		
1	Deike, G. H.	Draeger, model 1911 (mouth breathing).	1.84	70	18	8	27.48	0.21	Inspiratory bag	Both inspiratory and expiratory bag flat. Wearer in much distress; had a headache; could not get air enough; pulse rose from 72 to 140; respiration rose from 17 to 40.
						12	23.13	.10	do	
						14	20.80	.17	do	
2	McElroy, G. E.	do	2.00	64	24	10	26.16	.51	do	Both bags nearly flat toward end of test; otherwise wearer made no complaint.
						17	28.50	.26	do	
3	German, W. J.	do	2.92	75	17	8	35.25	.40	do	Both bags nearly flat.
						16	24.17	.40	do	
4	McElroy G. E.	Draeger, model 1911 (helmet).	2.00	64	8	6	20.73	.69	do	Wearer had to stop experiment; showed great distress; dizzy; at first only inspiratory bag was flat; later both bags were flat; pulse rose from 80 to 140; respiration rose from 20 to 40. High carbon dioxide content in helmet caused panting; breathing exceeded air circulation; then oxygen supply insufficient.
						7	18.81	3.36	Helmet	
						8	30.01	.20	Inspiratory bag	
5	Deike, G. H.	do	3.09	75	25	10	22.50	1.20	do	Wearer's knees almost gave way; looked ill; had headache; note high carbon-dioxide content in helmet.
						11	20.15	2.70	Helmet	
						18	25.80	.74	Inspiratory bag	
						19	23.50	2.60	Helmet	
6	German, W. J.	Fleuss	1.81	....	6	6	14.40	.75	Inspiratory bag	Both inspiratory and expiratory bag flat; wearer did not shake bag or use by-pass; wearer showed much distress; had to stop; pulse rose from 89 to 130; respiration rose from 19 to 44; insufficient oxygen.
7	Do.	do	1.81	....	6	5	18.80	.20	do	Both inspiratory and expiratory bag flat; wearer could not get air; shook bag, but did not use by-pass.
8	Do.	do	1.81	....	9	9	10.54	.54	do	Both bags flat; wearer had to stop; weak in knees; did not shake bag nor work by-pass; insufficient oxygen, also too much nitrogen (air) in bags to begin with.
9	Do.	do	1.81	....	8	7	26.40	.10	do	Wearer shook bag and worked by-pass repeatedly; could have continued experiment if not tired.

10	E. D. H.	do.	1.81		13	9	9.58	1.31	do.	Wearer did not shake bag, but worked by-pass 11 times; had to stop; in great distress; pulse rose from 80 to 152; respiration rose from 20 to 36. Too much nitrogen (air) in bags at start; insufficient oxygen flow; oxygen percentage was constantly too low to support life, much less permit hard work.
						13	8.41	2.02	do.	
10	Raudenbush, W. A.	do.	1.85		9	5	38.83	.13	do.	Although constantly shaking the bags, the wearer was able to continue after first two minutes only by repeated use of by-pass.
						9	31.32	1.55	do.	
11	McElroy, G. E.	do.	3.06		16	10	82.40	.70	do.	Wearer shook bag repeatedly, but did not use blow-off or by-pass. Both inspiratory and expiratory bag fairly well filled; air in bags uncomfortably hot; wearer was in fair condition for hard work.
						15	77.90	1.00	do.	
12	German, W. J.	Westfalia	2.20	60	19	10	20.70	1.00	do.	Both bags fairly well filled; condition of subject good.
						16	27.10	.80	do.	
						19	31.40	1.00	do.	

TABLE 7.—*Results of testing capacity of breathing apparatus to keep carbon dioxide content down to breathable amounts and to supply a sufficient volume of air during vigorous exercise.*

[The wearers walked 10 minutes at 3 miles per hour, 10 minutes at 4 miles, and then as long as they could—in no case more than 5 minutes—at 5 miles.]

Test No.	Apparatus used.	Oxygen flow per minute.	Volume of air in circulation per minute.	Rate of walking, miles per hour.	Sample of inspired air.			Remarks.
					Time taken, minutes from beginning of test.	Oxygen content.	Carbon-dioxide content.	
		Liters.	*Liters.*			*Per cent.*	*Per cent.*	
1	Fleuss	2.5	....	3	10	55.51	2.72	Bag not shaken; was filled with oxygen at start of 5-mile pace; bag full during test. After 23 minutes wearer was staggering; could not continue; high carbon dioxide.
				4	20	62.35	5.30	
				5	23	68.06	7.80	
2	Draeger, model 1911	2.5	75	3	10	44.62	.19	Both bags full for 20 minutes, but flat at finish; volume of air insufficient to continue test; wearer exhausted.
				4	20	38.39	.19	
				5	26	16.24	.59	
3	Westfalia, model 1913 (positive pressure).	2.0	70	3	10	67.00	2.50	Both bags full at end of 10 minutes; half full after 20 minutes; flat at finish. Insufficient volume of air; high carbon dioxide content; wearer staggering and exhausted; could not continue.
				4	20	70.00	5.32	
				5	23	55.00	7.55	
4	Westfalia, model 1913	2.0	72	3	10	44.56	.50	Both bags full for 20 minutes; at finish inhalation bag was flat, exhalation bag full. Subject staggering, dizzy, exhausted; insufficient volume of air; high carbon dioxide content; rate of respiration, 48 per minute.
				4	20	56.97	.95	
				5	25	43.78	6.07	

TABLE 8.—*Results of testing length of time that apparatus will supply breathable air under moderate exertion varied with periods of rest and vigorous exercise.*

[The subjects walked 15 minutes at the 3-mile pace, 7 minutes at the 4-mile pace, 3 minutes at the 5-mile pace, stood still 5 minutes, and repeated this cycle until the oxygen gave out. Experiments were performed Aug. 30, 1915, at Manitou, Colo., 6,000 feet above sea level; barometer 23.95, temperature 71.3° F. with dry-bulb thermometer, and 59° F. wet-bulb.]

Test No.	Wearer.	Apparatus used.	Oxygen flow per minute.	Volume of air in circulation per minute.	Oxygen gage at beginning and end of test.	Inspired air.				Pulse.	Respiration.	Remarks.
						Time sample was taken, minutes after starting test.	Oxygen content.	Carbon dioxide content.	Temperature.			
			Liters.	*Liters.*	*Atmospheres.*		*Per cent.*	*Per cent.*				
1	Parker, G. B......	Gibbs.........	....	....	125	25	63.2	0.6	....	150	30	Comfortable.
					....	55	64.0	1.2	....	144	30	Do.
					....	85	61.6	1.4	....	138	25	Do.
					....	115	60.8	1.8	....	144	30	Do.
					43	141	58.0	6.2	Cool........	144	48	Distressed by high carbon dioxide content.
2	East, J. H........	Fleuss........	3	....	118	25	88.2	.4	....	141	21	Bags shaken and blow-off used frequently.
					....	55	99.0	.6	....	141	21	
					....	85	....	1.0	Hot (134° F.)	120	31	
					2.5	120	96.0	.4	....	105	33	Oxygen supply exhausted.
3	Parker, G. B......	Draeger.......	2.5	74	130	25	82.8	.4	....	132	24	Comfortable.
					....	55	88.4	2.6	....	124	24	Do.
					35	90	87.0	7.0	Warm......	132	44	Distressed by high carbon dioxide content.
4	East, J. H........	Westfalia.....	2.5	80	125	25	67.0	.8	....	126	28	Comfortable.
					....	55	68.2	1.8	Not noticeably warm (83° F.).	120	28	Do.
					....	85	84.4	1.0		116	21	Do.
					5	115	84.0	1.4		120	24	Do.
					....	120	....	....	....	....	....	Oxygen supply exhausted.

Remarks.—These tests show that with the self-adjusting oxygen feed of the Gibbs apparatus (test 1) only 66 per cent of the oxygen supply was consumed in 141 minutes, whereas in the apparatus with the oxygen flow fixed at 2.5 or 3.0 liters per minute (tests 2 and 4) the supply was exhausted in 120 minutes. As the oxygen consumption (calculated from capacity of cylinder and fall of gage) in test 1 averaged 1.24 liters per minute, more than half of the oxygen in the fixed-feed apparatus was blown off and wasted, yet if the flow had been set at only 1.24 liters the wearers could not have endured traveling at paces of 4 miles for 7 minutes and 5 miles for 3 minutes every half hour.

The absorber of the Gibbs apparatus gave out only after 141 minutes. That of the Draeger (test 3) began to fail within 55 minutes and was exhausted in 90 minutes. The air in the Fleuss developed an excessively high temperature—134° F.

The high pulse rates in test 1 were probably due to the fact that the Gibbs apparatus in the incomplete form used for these tests did not fit comfortably on the back and had to be steadied with the hand. The absorber used in this test was also much below the average, as the air of the Gibbs apparatus having the later model of absorber usually shows less than 0.5 per cent carbon dioxide.

DISCUSSION OF RESULTS OF TESTS.

The results as shown in Table 3 of tests performed in the smoke room and in Table 4 of tests in which the subjects walked at 2 miles per hour in the open air demonstrate that an oxygen supply of 1,800 c.c. per minute is adequate and affords a considerable factor of safety for the energy expenditure involved in these conditions. From the results in these two tables as regards oxygen consumption and carbon dioxide output, it is fair to conclude that as a rule the total energy expenditure during training in a smoke room does not greatly exceed that of the "2 miles an hour" test. On the other hand, the results in the smoke room (Table 3) indicate an energy expenditure and an oxygen consumption considerably less than was obtained when the men walked at 4 miles per hour (Table 5). These facts afford the principal justification for the performance, in addition to training in a smoke room, of the tests in the open air where vigorous exertion can be required.

As seen in Table 5, at a pace of 4 miles an hour any rate of oxygen supply less than 2,200 c.c. per minute is liable to prove insufficient. For a pace of 5 miles an hour, as shown in Table 6, nearly 3 liters per minute is essential to meet the wearer's needs and to insure a fair margin of safety. Of course a miner never walks 5 miles an hour, but the exertion required by such a pace is no greater, in fact it is less, than he may make for a few minutes at a time during an emergency.

From these results it appears that in order to be safe the rate of oxygen supply in any apparatus that is set to a uniform flow should be not less than 3,000 c.c. per minute (measured at 20° C. or 68° F.) as a minimum.

To this, however, there are two serious objections. The first is that the breathing bag or bags are constantly overfilled when the subject is not greatly exerting himself. It is necessary therefore to provide a blow-off or escape valve for the excess oxygen, and unless the valve works easily an annoying resistance to expiration results. The second is that during a period of rest or of moderate exertion as much as two-thirds or three-fourths of the oxygen supply wastes through this valve. The length of time that the oxygen will last is correspondingly reduced.

The importance of this last consideration may be seen in Table 8, in which a man wearing the Gibbs apparatus with self-adjusting oxygen feed had consumed only two-thirds of his supply in 141 minutes, whereas in the Fleuss and Westfalia apparatus, with the feed set at 2.5 and 3 liters respectively, the same initial supply of oxygen was exhausted in 120 minutes.

An even more important observation is that afforded by the endurance test with the Draeger apparatus (Table 8), in which the capacity of the absorber to purify the air was exhausted and the carbon dioxide was rising to intolerable amounts after only 90 minutes. There is no advantage in having the wearer of breathing apparatus carry enough oxygen to last for a considerable time, if he may become asphyxiated with carbon dioxide before the oxygen is used.

The twin bottles of the Draeger apparatus have a capacity together of 2.6 liters, those of the Westfalia approximately the same, that of the Fleuss 2.36 liters, and the Draeger single bottle a capacity of 1.9 to 2.0 liters. The bottles are charged with oxygen to a pressure of approximately 120 atmospheres. Calculated from these figures the Fleuss is capable of supplying about 280 liters of oxygen, the Draeger single bottle 225 liters, and the Draeger and Westfalia twin bottles about 310 liters.

The fact that the oxygen lasted much longer in the endurance tests than would be expected from these figures for the initial supply divided by the volume of feed per minute is probably due to a diminishing flow under diminishing pressure during the latter part of the tests. Herein also is to be seen a defect of the fixed-feed type of apparatus, as compared with the self-adjusting feed as in the Gibbs apparatus.

With any form of apparatus the breathing bag or bags should be filled at the beginning with as little outside air and as nearly pure oxygen from the tank as possible. The tables show that the oxygen in the breathing bag rarely rose above 80 per cent. In some instances it fell below 20 per cent, and in a few significant cases when the wearer was nearing collapse it was below 10 per cent. These figures indicate that a considerable volume of nitrogen had been left from the air contained within the apparatus and in the wearer's lungs at the beginning of the test. When the test was begun with the bags filled merely with air, which contains approximately 79 per cent of nitrogen, the atmosphere which the subject breathed was almost constantly below 20 per cent and frequently fell below the danger limit of 13 per cent.

Furthermore, owing to the fact that the oxygen in the tanks is usually diluted with at least 2 to 3 per cent of nitrogen—in one instance nearly 5 per cent was found—and that this nitrogen accumulates in the apparatus as the oxygen is consumed, it is best even with an apparatus in which the oxygen flow is automatically adjusted to the wearer's breathing to arrange that there shall be constantly a very slight positive pressure—not more than 1.5 centimeters or half an inch water gage. This slight pressure insures a constant slight escape of air from the apparatus through the blow-off valve or through any cracks or leaks that may develop. The oxygen cylinders of ordinary size filled at the pressure usually employed contain approximately 280 liters of gas. Of this 2 to 3 per cent, or 5.6 to 8.4 liters, is nitrogen, an amount more than sufficient to fill the bags and induce asphyxia if there is no blowing off to prevent accumulation.

In a number of the tests given in Tables 3 to 8 it will be noted that the oxygen percentage progressively increased. This indicates a sweeping out of the nitrogen from the apparatus, owing to a continual leakage outward, or to blowing off the excess of air in the bags through the relief valves. In other cases in which the breathing bags continued well distended but the oxygen percentage fell—that is, the amount of nitrogen increased—the evidence indicates that a considerable volume of outside air leaked into or was sucked into the apparatus—a most significant fact in explaining the deaths from carbon monoxide poisoning in men wearing apparatus in mines after explosions or fires. It emphasizes the importance of having conditions which will insure leakage outward.

To the suggestion that the bags should be filled with as nearly pure oxygen as possible the objection may be made that the breathing of pure oxygen for several hours has been shown to have a marked irritating effect upon the lungs.[a]

In fact oxygen becomes extremely poisonous at pressures of several atmospheres, such as are necessary in some forms of diving apparatus similar to mine rescue apparatus. In mine rescue apparatus, however, except when used in compressed air as in caissons or submarine tunneling, no such pressures can occur. Furthermore mine rescue apparatus is rarely worn more than 2 or 3 hours at a time, and even when there is an excess oxygen supply and the bags are initially filled with oxygen instead of with air, the proportion of oxygen in the breathing bag does not often exceed 75 to 80 per cent. The experience of the rescue crews of the Bureau of Mines in practical work, and the observations made during the tests reported in this paper, have given no indication of any deleterious effects from such amounts. The slight tendency which these conditions may have to irritate the lungs is negligible compared with the advantage of reducing to the utmost the risk of an insufficient oxygen supply. The only way to make absolutely sure that there shall never be a deficiency is to provide for an excess at all times.

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[a] See Hill, L., Recent advances in physiology and biochemistry, London, 1908, p. 239. See, also, Karsner, H. T., Pathologic effects of atmospheres rich in oxygen: Jour. Experimental Medicine, vol. 23, 1916, p. 149.

DANGER OF USING OXYGEN CONTAINING HYDROGEN AND NITROGEN IN EXCESSIVE AMOUNT.

Oxygen is now extensively produced electrolytically, and such oxygen may, when not properly prepared, contain considerable amounts of hydrogen. As the hydrogen is not absorbed in breathing, it will accumulate in the breathing bag, and may, when it originally comprised more than 0.5 per cent, reach explosive proportions before the end of a 2-hour period. Evidently oxygen having more than a trace of hydrogen should not be used in rescue apparatus.

It has recently been brought to the attention of the bureau, through a series of explosions in oxygen tanks, that commercial oxygen contains a serious amount of impurity. Samples gathered from various parts of the country show that the explosions have been caused by the presence of hydrogen in oxygen which has been made by the electrolytic process. Oxygen is produced electrolytically at many different plants throughout the United States, and some of these plants have not guarded their manufacturing processes sufficiently to prevent hydrogen getting into the oxygen produced for local use or for shipping.

It appears that the presence of hydrogen is due in many cases to the sudden shifting of polarity in the electrolytic cells. In the more carefully arranged plants the oxygen produced goes into a bell or receiver, from which at frequent intervals samples are taken for analysis, and if hydrogen is found in appreciable amount the oxygen in the tank is discharged into the open air, but, if practically pure, is compressed and is then used either locally or placed in cylinders under high pressure for shipment. The lower explosive limit of a hydrogen-oxygen mixture is 10 per cent, although according to tests by G. A. Burrell, formerly of the Bureau of Mines, mixtures containing as low as 7 or 8 per cent hydrogen develop considerable pressure when ignited.

The many violent explosions which have occurred in oxygen tanks in various parts of the country, in conjunction with or as a result of the use of the oxyhydrogen or oxyacetylene flame, have demonstrated that in many instances commercial oxygen has been shipped or used direct which contained more than 10 per cent of hydrogen. Apart from the danger of explosions when such oxygen is used, through ignition by various means, its use is a serious source of danger in self-contained mine rescue apparatus from the hydrogen causing oxygen deficiency in the apparatus after it has been worn for a period.

The subject will be more fully discussed in subsequent publications of the bureau after the investigations now under way have been completed, but it is important, in considering the physiological effects on users of breathing apparatus, to note certain results. 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 1 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.

Under these conditions the gases in the circulatory system were deficient in oxygen, and also were explosive; and if an open light had been brought near a discharge valve with such an internal atmosphere, an explosion would have resulted, which would undoubtedly have been fatal to the wearer.

Hydrogen itself has no poisonous effect, but through its steady accumulation in the circulatory system, owing to the fact that it is absorbed neither in the lungs nor by the chemicals (caustic soda), the percentage steadily increases to an extent which may cause oxygen deficiency in the apparatus, and hence is dangerous to the wearer, as described elsewhere in this publication.

Oxygen made by liquefaction processes is not likely to have hydrogen in it, but it is practically impossible to obtain oxygen by this process that is free from nitrogen. Some of the samples gathered from oxygen tanks furnished the bureau have shown as high as 4 or 5 per cent nitrogen. Nitrogen, like hydrogen, may accumulate in the circulatory system of the rescue apparatus, and, although free from danger of explosion, may cause oxygen deficiency when the apparatus is being used to the limit of its capacity. Accordingly, the bureau has tentatively specified to manufacturers who supply oxygen for its mine rescue apparatus that the oxygen shall not contain more than 2.5 per cent nitrogen nor more than 0.2 per cent hydrogen.

As an additional precaution all mine rescue apparatus should be fitted with a blow-off valve so that from time to time some of the air in the circulatory system is discharged, in order to prevent the accumulation of the inert gases, hydrogen and nitrogen. The Draeger and the Westfalia apparatus have automatic relief valves, and as they have a fixed oxygen feed, are not likely to accumulate nitrogen or hydrogen unless the wearer is vigorously exerting himself so that the breathing bags are kept almost continuously deflated.

The Fleuss-Proto apparatus has a relief valve which is not automatic and has to be pressed open by hand. It is possible therefore that unless the wearer flushes out the bag once in a while, by pressing on the bag and opening the relief valve, hydrogen or nitrogen, if in excess, may accumulate.

When the Gibbs apparatus was first constructed, it did not have any relief valve, and, having an automatic feed valve, was particularly liable to accumulate either nitrogen or hydrogen. But a valve which bleeds a little has been introduced, and this will keep the hydrogen and nitrogen flushed out of the apparatus.

In conjunction with the flushing of the Fleuss-Proto apparatus when in use, it has been found by one of the bureau investigators that care must be exercised, after squeezing the bag, to immediately close the relief valve, as otherwise there is a suction action, and the outside atmosphere is drawn into the bag.

CARBON DIOXIDE ABSORPTION IN TESTS OF APPARATUS.

It will be seen from Tables 3 to 8 that the tests of apparatus are more often brought to an end by the development of a high percentage of carbon dioxide than by any one other cause. In experiments with relatively moderate exertion, such as in those represented in Tables 3 and 4, this defect is much less evident than with more vigorous exertion, as in the experiments represented in Tables 5, 6, and 7.

The peculiar disadvantage of the helmet is shown by the fact that even during moderate exertion and with an oxygen supply and circulation sufficient to keep the air in the breathing bags at an ideal composition, the gas samples drawn from the helmet contained more than 2 per cent of carbon dioxide. During more vigorous exertion the air in the helmet contained in many cases between 3 and 4 per cent of carbon dioxide and quickly produced marked distress and subsequent headache, whereas that from the inspiratory bag showed a composition such that if the subject had been inhaling through a mouthpiece there would have been no discomfort, and the test would not have had to be discontinued.

In several cases during vigorous exertion with Draeger apparatus of the mouth-breathing type the inspiratory bag was drawn flat even when the circulation of air was 70 to 75 liters per minute, indicating that the wearer was breathing more than this amount. As 75 liters is, however, about the maximum obtainable with artificial circulation, these observations reinforce the other objections to this device, as compared with the arrangement by which the wearer's breathing supplies the force that sends the exhaled air through the carbon dioxide absorber.

The figures obtained from the Fleuss apparatus indicate that the absorption of carbon dioxide soon becomes unsatisfactory unless the bag is shaken frequently so as to knock off the accumulation of carbonate upon the sticks of sodium hydroxide. With frequent shaking the carbon dioxide was usually kept down to a fairly satisfactory proportion. The manufacturers, in fact, direct that the bag should be shaken frequently. This necessity is not an insuperable objection to this apparatus, as an excess of carbon dioxide in the air breathed, unlike an oxygen deficiency, invariably produces such heavy breathing that the wearer is warned in time. Nevertheless, it is a handicap on the wearer's ability to work.

The endurance of the various absorbers is shown best in Table 8, which summarizes the results obtained when the men wearing the apparatus went through tests in which they walked for 15 minutes at the 3-mile pace, for 7 minutes at the 4-mile, then ran for 3 minutes at the 5-mile pace, and after a rest of 5 minutes (or 30 minutes in all) repeated the performance until compelled to stop by the failure of the apparatus in one respect or another.

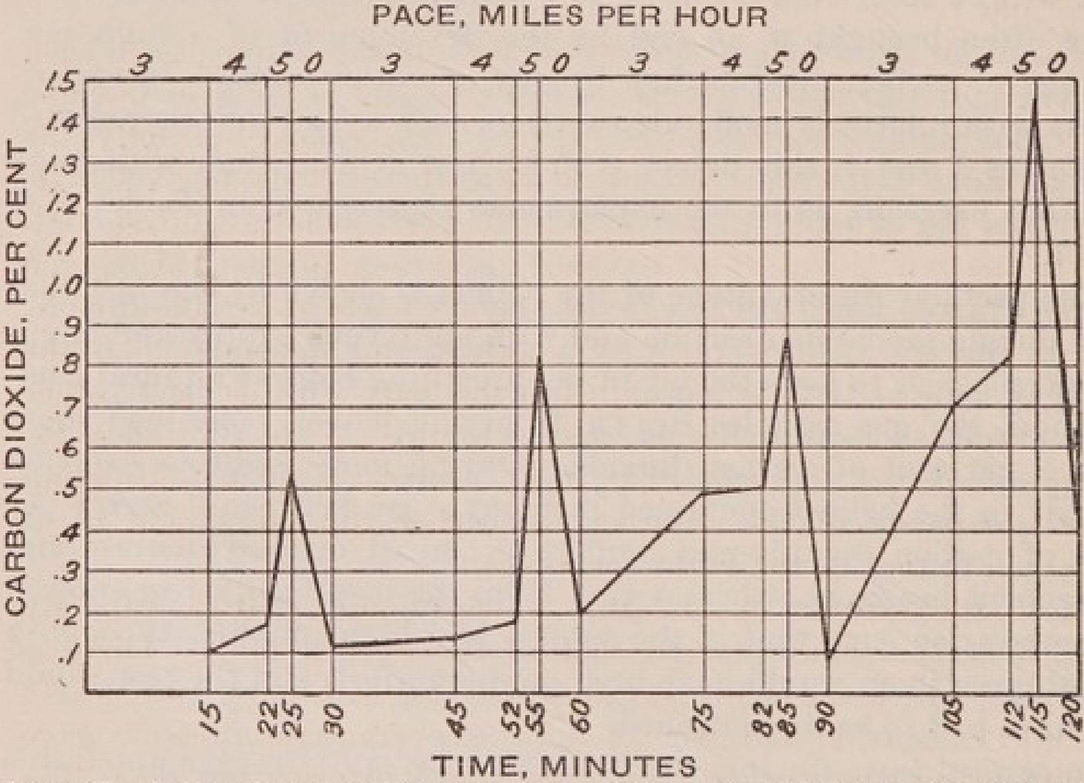

FIGURE 5.—Curves showing efficiency of carbon dioxide absorption in the Gibbs apparatus at various rates of walking.

The results demonstrate that in the Fleuss, with repeated shaking of the bag, assisted by frequent blowing off of excess oxygen, the alkali was still absorbing efficiently, although uncomfortably hot, after 120 minutes, when the oxygen supply was exhausted. In the Draeger, on the other hand, although the absorption was, and as shown in previous tests usually is, extremely good during the first hour, the efficiency fell off rapidly after this time. The test was terminated after only 90 minutes, because of the excessive accumulation of carbon dioxide. In the Gibbs apparatus the absorbing can was then in a somewhat experimental stage, and the test quoted in Table 8 shows a much poorer efficiency than in most similar tests performed with this apparatus. Even so, the absorber retained a considerable degree of efficiency up to 140 minutes, when it failed rather suddenly. The results of a recent experiment of this sort, performed at the experiment station of the bureau at Pittsburgh, with the Gibbs apparatus, are plotted in figure 5. The curve shows the percentages of carbon dioxide in the air of the bellows of the apparatus throughout a 2-hour endurance test in which the wearer walked 15 minutes at 3 miles an hour, 7 minutes at 4 miles, ran 3 minutes at 5 miles, and rested 5 minutes, repeating this cycle every 30 minutes.

Efficiency in an absorber depends of course primarily on the surface of alkali exposed. The endurance depends not merely upon the total amount of alkali in the absorber, but also upon the proportion of the part converted into carbonate to the part that becomes coated and remains unused in the hydroxide form.

It is self-evident that in any apparatus of the automatic oxygen feed type, in which the oxygen is made to last as long as possible by feeding into the apparatus (apart from leakage) exactly the amounts needed, the absorber should have the capacity to fix a little more than the amount of carbon dioxide corresponding physiologically to the initial supply of oxygen. For each 10 parts of oxygen absorbed by the lungs a man exhales about 8 parts of carbon dioxide. This is the so-called respiratory quotient and depends upon the fact that some of the oxygen unites in the body with elements other than carbon, such as hydrogen and sulphur. With allowance for leakage of oxygen, it seems that in an apparatus of self-adjusting feed the capacity of the absorber for carbon dioxide should be at least equal to that of the tanks for oxygen.

Indeed, there is one consideration which suggests that the capacity of the absorber should exceed that of the oxygen tank. There is no way by which the wearer of an apparatus can know how nearly the absorber is exhausted, whereas on the contrary the pressure gage or finimeter on the oxygen tank does afford information regarding the oxygen supply. Evidently the finimeter is a safe indicator as to how long a man may stay in bad air, only on the condition that the absorber is not liable to fail first, and the wearer be suffocated with carbon dioxide.

As ordinarily charged at 120 atmospheres, the oxygen cylinders are capable of supplying about 280 liters at atmospheric temperature. To absorb the corresponding amount of carbon dioxide requires about 2.1 pounds of sodium hydroxide or 2.9 pounds of potassium hydroxide, assuming that all of the alkali is combined to form carbonate, which, of course, is a practical impossibility. The results of somewhat elaborate tests as to the weight of alkali, surface exposed, and percentage of alkali combined in the various apparatus are summarized in Table 9.

TABLE 9.—*Results of tests with breathing apparatus showing the amount of alkali, surface exposed, and percentage of alkali combined as carbonate in the various types of absorber.*

Apparatus.	Weight of alkali.	Surface exposed.	Percentage of alkali combined as carbonate.
	Pounds.	*Square feet.*	
Fleuss	4.0	4.0	15+
Draeger	2.2	9.47	30 to 45
Westfalia	1.7	7.15	25 to 60
Gibbs	4.0	18.0	35 to 40

In the tests with both the Draeger and the Westfalia, particularly the latter, the alkali contained a considerable amount of potassium hydroxide. This may have increased the efficiency but reduced the total capacity for carbon dioxide below that of pure sodium hydroxide. In the test with the Fleuss the percentage of alkali combined could have been greatly increased by continual shaking of the bag.

From these data it appears that in the Draeger and the Westfalia, for which the figures here reported are approximately the extremes of many analyses, the capacity to absorb carbon dioxide is less than one-half, and probably nearer to one-third, equivalent to the capacity for oxygen supply. It is probable that for the Draeger absorber 100 liters of carbon dioxide is the maximum. It is only fair to add, however, that the tests reported in this paper indicate that while the alkali in the absorption cartridge lasts, the Draeger absorber is very efficient in keeping the carbon dioxide down to small amounts.

The Fleuss has considerably greater total capacity to absorb carbon dioxide than either the Draeger or the Westfalia, although the fact is not evident from the single analysis here reported, but it does not, in most tests, keep the carbon dioxide content in the air passing through it as low as do the other types, owing to the restricted surface exposed becoming covered with the carbonate. Both the efficiency and the total capacity of the Fleuss depend to a very large extent upon the frequency with which the bag containing the sticks of sodium hydroxide is shaken.

In the Gibbs apparatus the comparatively high percentage efficiency—the minimum is higher than that of the other apparatus—depends on the fact that the surface of the plates slowly liquefies and runs down into the bottom of the can, thus continually affording a fresh moist surface of alkali. In this apparatus, however, the details as to the amount of alkali to be carried, and the amount of water to be crystallized in the plates, are not yet entirely settled.

THE SIMPLEST METHOD OF TESTING ABSORBERS.

Such data as the foregoing, although of some value as showing the maximum capacity of an absorber, are nevertheless of less practical significance than the figures obtained from analyses showing the percentage of carbon dioxide in the air which has passed through the absorber. It is what an absorber does, and how long it does it, not what it contains, that counts. For determining this with the least discomfort to the wearer, and with the least expense, a method used by Mr. Gibbs is simple and adequate.

For this test the wearer is provided merely with a mouthpiece, connected with inspiratory and expiratory valves, and the absorber to be tested. While walking at a convenient pace, he inspires outside air through one valve and exhales through the other into the absorber, from which the breath escapes to the atmosphere. Samples of the air that have passed through the absorber are collected at regular intervals, and the results are plotted. Figure 6 shows the results of

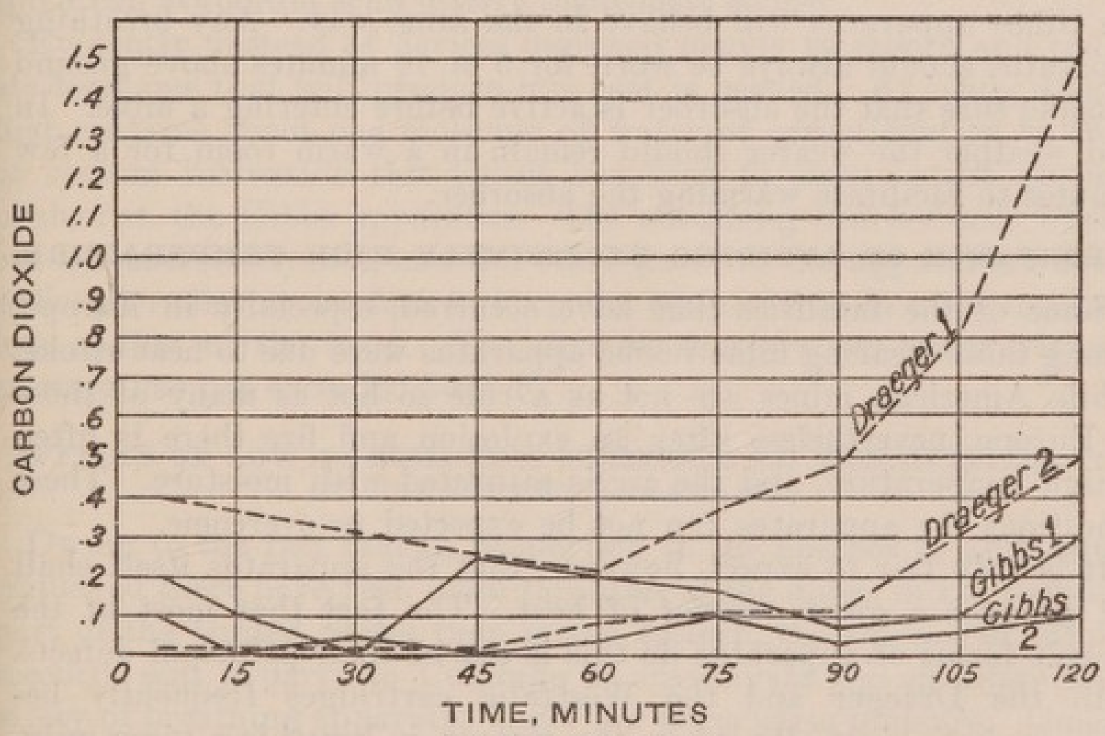

FIGURE 6.—Curves showing relative efficiency of absorbers in Draeger and Gibbs apparatus. Maximum temperature of absorber: Draeger, 258° F.; Gibbs, 193° F. Maximum temperature of air leaving absorber: Draeger, 210° F.; Gibbs, 150° F.

four such tests, two with the Draeger absorber and two with that of the Gibbs apparatus on a man weighing 180 pounds, while walking steadily at 3.8 miles per hour. The Gibbs absorber is shown here to exceed the Draeger only slightly in efficiency, but greatly in endurance. It is also noteworthy that the temperatures observed both in the interior of the absorbers and at the effluents were considerably higher in the Draeger than in the Gibbs apparatus. In some tests of this sort with the Draeger so much heat was developed that the alkali fused and blocked the passages of the absorber.

As the fusion or liquefaction of the alkali may allow it to run together into a few large masses and thus destroy the efficiency of the absorber, it would be well to subject every new absorber that may be devised to tests in the hot room of a Turkish bath or some place of corresponding temperature.

DEFICIENT ABSORPTION OF CARBON DIOXIDE AT LOW TEMPERATURES.

The production and retention of much heat in the absorbers now in use is a disadvantage, but a certain amount of it is not only unavoidable but even useful. Experience has shown that in mines in the Northwest, where the temperature above ground in the winter may be extremely low, if the apparatus is put on cold, carbon dioxide may accumulate in sufficient quantity to overcome the wearer before the caustic soda, or other chemical used, becomes warm enough to absorb effectively. It is probable that the absorber employed in the Gibbs apparatus will behave in the same way. Any breathing apparatus should always be worn for 5 or 10 minutes above ground to make sure that the absorber is active before entering a mine. In cold weather the wearer should remain in a warm room for a few minutes to facilitate warming the absorber.

IMPORTANCE OF AVOIDING EXCESSIVELY HIGH TEMPERATURE.

Some of the fatalities that have occurred, especially in Europe, among those wearing mine rescue apparatus were due to heat stroke. While American mines are not as a rule so hot as many of those in Europe, nevertheless after an explosion and fire there is often a high temperature, and the air is saturated with moisture. These conditions the apparatus can not be expected to overcome.

It is only fair to expect, however, that the apparatus itself shall not produce a great amount of heat. The fact that most of the present forms of apparatus do this is one of their principal defects. Both the Draeger and the Westfalia cartridges frequently become so hot, especially when the wearer is breathing vigorously, that they can not be touched with the hand. On this account they are carefully insulated from the wearer's back to prevent severe burns. In the Fleuss apparatus the large mass of sodium hydroxide carried in the bag becomes hot enough to drive off water from the carbonate formed as carbon dioxide is absorbed. The air that the subject inhales thus becomes saturated with moisture at a temperature higher than that of the body. Some of the moisture condenses in the mouth and throat and gives off its latent heat. Various devices have been used to decrease this defect. Those which depend on the evaporation of a small amount of alcohol placed around a box on the inspiratory tube are much too small and of too temporary an action to be of any value. In a recent model of the Fleuss an extra compartment in the breathing bag is provided, in which a couple of pounds of sodium sulphate ($Na_2SO_4+10H_2O$) is carried.

This crystalline substance liquefies at about 90° F. with a considerable absorption of heat. The device was brought out after the experiments here reported had been completed.

In the Draeger and the Westfalia the metal radiators or coolers, through which the air circulates after passing through the carbon dioxide absorber, are fairly effective in eliminating heat. It has been found that when the wearers were performing moderate exertion at ordinary temperatures, 60° to 80° F., the temperature of the inspired air is usually about 10° higher than atmospheric. In the Fleuss, however, the air inspired sometimes reaches a temperature as high as 140° F., even during tests in open air. The small saliva trap over which alcohol is held by a cloth in the Fleuss so that the spirit can evaporate is an utterly inadequate cooler.

Evidently, instead of devices designed merely to absorb and radiate heat, one that will produce less heat is needed. By using alkali that contains about one molecule of water of crystallization to two of sodium hydroxide this object has been to some extent accomplished in the Gibbs apparatus. The absorbing can becomes warm but not excessively hot, and the other parts of the apparatus afford sufficient radiating surface to keep the temperature in most cases as low as that of the body. The extreme temperature under violent exercise has not exceeded 102° F.

EFFECTS OF LOW BAROMETRIC PRESSURE ON THE EFFICIENCY OF BREATHING APPARATUS.

Owing to the fact that in proportion to the number of apparatus employed there have been more fatalities in the mines in the western part of the United States than in the eastern, the Bureau of Mines recently sent a party to Colorado to investigate the efficiency and safety of breathing apparatus under low barometric pressure. Under the direction of the authors extensive series of tests were carried out with all four of the types of apparatus dealt with in this report, at Manitou, altitude 6,000 feet, barometer 23.95; at the Half-Way House on Pikes Peak, 8,950 feet above sea level, barometer 21.876; and at the summit of Pikes Peak, altitude 14,090 feet, barometer 18.04.

Examples of the experiments performed at Manitou have already been discussed in connection with Table 8. They show no perceptible deviation from the behavior of the apparatus in similar tests at the experiment station in Pittsburgh and in New York and New Haven at sea level. The experiments carried out at the Half-Way House and at the summit of Pikes Peak are summarized in Table 10. They demonstrate conclusively that apparatus which is in good order works quite as efficiently at an altitude of 5,000 or 10,000 or even 14,000 feet above sea level as it does at ordinary barometric pressure.

TABLE 10.—*Results of tests with breathing apparatus at high altitudes.*

[The tests show that breathing apparatus works quite as well at these altitudes as at lower places, and that the helmet is as objectionable here as elsewhere. After the subject had performed the test with the apparatus, the mouthpiece was removed and he walked or ran back and forth while breathing the outside air. Owing to the low barometric pressure (insufficient oxygen) the subject was in all cases badly winded within 2 minutes under these conditions by an exertion which he had made easily when breathing the high oxygen atmosphere afforded by the apparatus.]

HALF-WAY HOUSE ON PIKES PEAK, 8,950 FEET ABOVE SEA LEVEL, BAROMETER, 21.876.

Test No.	Wearer.	Apparatus.	Oxygen flow per minute.	Volume of air in circulation per minute.	Rate of walking, miles per hour.	Duration of test.	Proportion in inspired air. O$_2$.	Proportion in inspired air. CO$_2$.	Pulse.	Respiration.	Remarks.
			Liters.	*Liters.*		*Minutes.*	*Per cent.*	*Per cent.*			
1	Henderson, Yandell.	Gibbs			0				80		Standing still.
					4	10	54.2	0.2	124	20	Walking easily.
					5	7	59.6	.2	144	30	Running easily.
					5	2			160	44	Breathing outside air; distressed.
2	East, J. H.	do			0				68		Standing still.
					5	10	72.2	.2	144	28	Running easily.
					5	2			160	40	Breathing outside air; distressed.
3	Parker, G. B.	Draeger	2.5	74	0				80		Standing still.
					4	10	73.0	.3	120	24	Walking easily.
					5	10	65.8	.6	152	24	Running easily.
					5	2			160	48	Breathing outside air; distressed.
4	Reese, D.	Westfalia	2.7	80	0				100		Standing still.
					4	10	80.4	.6	156	26	Walking easily.
					5	7	75.8	1.0	176	32	Running easily.
					5	2			176	44	Breathing outside air; distressed.
5	East, J. H.	Fleuss	3.0		0				80		Standing still.
					4	10	70.6	.4	128	28	Walking easily.
					5	5	84.4	1.0	156	28	Running easily.

SUMMIT OF PIKES PEAK, 14,090 FEET ABOVE SEA LEVEL, BAROMETER, 18.040.

Test No.	Wearer.	Apparatus.	Oxygen flow per minute.	Volume of air in circulation per minute.	Rate of walking, miles per hour.	Duration of test.	Proportion in inspired air. O$_2$.	Proportion in inspired air. CO$_2$.	Pulse.	Respiration.	Remarks.
6	Paul, J. W.	Gibbs			0				68	16	Standing still.
					4	10	44.2	0.4	120	30	Walking easily.
					5	5	42.8	.6	150	32	Running easily.
					5	2			156	48	Breathing outside air; distressed.
7	East, J. H.	Draeger: With mouthpiece.	2.5	74	0				64		Standing still.
					4	5	76.4	.4	105	30	Walking easily.
					5	5	76.0	.6	150	30	Running easily.

		With helmet.......	2.5	74	4	3	27.0	2.2	132	42	Distressed.
					5	2	42.0	7.8	190	65	Staggering.
8.......	Reese, D..........	Westfalia:									
		With mouthpiece..	2.5	80	0	....	....	....	110	....	Standing still.
					4	5	55.2	.2	168	24	Walking easily.
					5	5	47.2	.8	168	24	Running easily.
		With helmet.......	2.5	80	4	3	....	....	156	36	Walking.
					5	3	18.2	5.2	180	36	Distressed.
9.......	East, J. H........	Fleuss................	3.0	....	0	....	....	....	96	....	Standing still.
					4	5	80.8	.8	150	30	Walking easily.
					5	3	85.2	.6	172	30	Running easily.

These experiments demonstrate the interesting fact that at the summit of Pikes Peak a man can do more work when wearing breathing apparatus than without it. With the apparatus, if the rate of oxygen flow is sufficient, his oxygen needs are fully supplied, and without discomfort vigorous exertion is possible, which, if made while breathing the outside air, would cause extreme breathlessness and distress because of the low atmospheric pressure and insufficient oxygen.

The probable explanation of most of the accidents that have occurred in the West is that the rubber parts of the apparatus, which have been bought and kept for an emergency, have deteriorated, developed cracks or breaks, and admitted carbon monoxide to the lungs of the wearer. Practically all of the accidents in western mines have occurred with the helmet type of apparatus. Rubber deteriorates much more rapidly in the dry western climate than in the Eastern States, and indeed everywhere in America more rapidly than in Europe. The inflatable rubber ring, which is supposed to make the helmet tight around the face, is necessarily made of elastic rubber and deteriorates rapidly. Even a slight stiffening renders it liable to develop grooves in the part below the chin, and even to burst when fully inflated.

THE NEED OF FREEDOM FROM MECHANICAL OBSTRUCTION TO BREATHING.

The importance of having all valves, tubing, and openings as large and as free from resistance as possible has not generally been adequately appreciated either by the manufacturers or the users of breathing apparatus. When one puts on any of the three forms of apparatus now used in America, he finds that he can breathe quietly back and forth into the bags without noticeable effort. Even if directed to breathe vigorously for a few seconds, most subjects declare that they feel no considerable resistance. If, however, the wearer is required to exert himself so vigorously as to induce heavy breathing, he finds a resistance so exceedingly annoying that it soon occupies his mind to the exclusion of everything else, and he is strongly tempted to tear off the apparatus.

When a water gage is attached to the mouthpiece, it shows that in moderate breathing the positive and negative pressures during inspiration and expiration do not exceed 3 to 5 centimeters (1.2 to 2 inches) water gage. The comparatively slow movements of the air allow it to pass through the tubes and valves with slight resistance. During heavy breathing, however, because of the increased rapidity of movement of the air, adverse pressures both positive and negative of as much as 10 to 15 centimeters water gage, or even more, are developed. The fatigue involved in breathing under such conditions is a serious matter. In one case a negative pressure of 22 centimeters was observed, an intolerable obstruction to respiration.

The reason why all three forms of apparatus, at least in their older models, have practically the same obstruction to breathing is that the mouthpiece and corrugated rubber tubes leading to the breathing bags of each are of about the same size. The tubes and valves have an interior diameter of 2 centimeters or a little less, too small to allow 3 liters of air to pass in a second without considerable friction. To meet this objection a form of the Fleuss apparatus has been devised for the London Fire Brigade, in which tubing of 2.5 centimeters (1 inch) interior diameter is used, and the valves are correspondingly larger. This feature is to be commended. All tubing, openings, and valves should, so far as possible, have a diameter when round of at least 2.5 centimeters and a cross section of 5 square centimeters, or 0.8 square inch.

Every apparatus before being worn under service conditions should be tested by means of a water manometer connected through a wide tube with the mouthpiece. The wearer should then inhale from and exhale into the bags as deeply and as rapidly as possible. The positive pressure so developed should not exceed 5 centimeters (2 inches) water gage, preferably not 2.5 centimeters, and the negative pressure should never exceed 2.5 centimeters.

DANGER OF BREATHING BAGS BEING BREATHED OR SQUEEZED EMPTY.

In a considerable proportion of all the fatalities among men wearing breathing apparatus the victim has been found to have torn off the helmet or mouthpiece. It is probable that in many of these cases the temptation to do this arose from an insufficient volume of air in the bags. One of the most terrifying sensations that a man can experience is to be unable to fill his lungs when he feels the need for breathing deeply. A man can hold his breath far better with full lungs than with them comparatively empty. Indeed the principal nerves of respiration, the pulmonary vagi, appear to be so strongly stimulated by the latter condition that the will power is scarcely sufficient to oppose them. Accordingly when the wearer of an apparatus experiences this sensation he is tempted to tear off the apparatus, even though he knows that the surrounding atmosphere is deadly.

This situation may arise from an insufficient oxygen supply coupled with considerable physical exertion. It arises in its most acute form, however, when the air is pressed out of the bags between the wearer's body and the ground when he is crawling through a low passageway. The bag may also be squeezed empty between the wearer's body and knees while he is crouching to pass under an obstruction.

It has been found in actual rescue and recovery operations that few of the men who have been trained observe their instructions under such conditions. Training and discipline are ignored and the thought uppermost seems to be to tear off the apparatus or to escape. As the man at the same time may be under the effects of insufficient oxygen, or of carbon monoxide which he may have sucked into the apparatus and inhaled, he is liable not to exercise his usual good sense.

On the other hand, men who have observed their training instructions have under such circumstances in many cases saved themselves by remaining calm, resting, and allowing the apparatus to "catch up" with their requirements. One of the authors on a number of occasions has been obliged to stop and rest, and to insist that his crew do likewise, so as to allow the supply of oxygen and the absorption of carbon dioxide to become sufficient for the wearer's needs.

It is an advantageous feature of the Fleuss apparatus that the mass of sodium hydroxide in the bag tends to prevent its being squeezed empty. Furthermore, the by-pass on the oxygen feed valve of this apparatus enables the wearer by turning a cock to refill the bags immediately. This feature should be included in all forms of breathing apparatus which are set to a uniform oxygen feed.

In the Gibbs apparatus the breathing bag has been replaced by a small bellows which is carried on the back and is so completely protected by a cover that it appears practically impossible for the bellows to be squeezed empty except by some very unusual accident. If the bellows is emptied, the feed valve reinflates it automatically and immediately.

JOINTS AND CONNECTIONS.

Safety demands that when the wearer of an apparatus is surrounded by an atmosphere containing poisonous gases there should be no leakage inward. With the injector type of apparatus it is particularly important that no negative pressure should occur at any point where the outside atmosphere may be drawn in. As formerly constructed the injector of the Draeger drew air through the absorber. In case the absorber or the tube leading to it was cracked poisonous gases could enter. A life has been lost in this way. This defect has been to a considerable extent remedied by so placing the injector of the Draeger apparatus that the air is forced through the absorber under a slight positive pressure. In any arrangement of this sort however there must always be a greater or less area of negative pressure on the side from which the injector draws. This is an additional reason for abolishing the artificial circulation and giving up the injector entirely. A natural circulation depending upon the respiratory movements of the wearer is altogether preferable.

It is an advantage to have a slight positive pressure in the apparatus, although it must of course not be of such amount as to impede the wearer's expiration—about 0.5 centimeter, or at most 1.0 centimeter, water gage. Even the best constructed apparatus is liable to leak slightly, and all leaks should be outward instead of inward. One of the principal reasons for recommending a greater supply of oxygen than is now used in apparatus of the fixed-feed type is the fact that there will then be a continual slight leakage outward of the excess. On the other hand when the oxygen supply is insufficient and the breathing bags are sucked flat at each breath the negative pressure so produced may draw in the surrounding poisonous atmosphere.

THE MOUTHPIECE.

Although the mouth-breathing types of apparatus are preferable to the helmet types, the rubber mouthpieces themselves as now made are far from perfect. The mouthpiece of the Fleuss apparatus has been found much more satisfactory than that formerly furnished with the Draeger or Westfalia. Recently, however, the manufacturers of the two latter forms of apparatus have improved the mouthpieces until they are almost the counterpart of the Fleuss.

It has been found even with the improved mouthpiece, such as the Fleuss, that the flange which fits inside the lips and cheeks and carries the lugs upon which the teeth are clenched is too small to insure complete tightness at all times. In a mouth of little more than the ordinary size it is comparatively easy, by merely retracting the corners of the lips, to leave a fairly large opening at each end of the flange. It has been found in many experiments that when the wearer of the apparatus was breathing deeply because of vigorous exertion it was impossible to prevent the distension of the mouth to such an extent that outside air was drawn in. The flange of the Fleuss should be about half a centimeter wider, that is higher and deeper, and 2 centimeters longer. It would be easy to cut the flange down if found too large for the mouth of the man who is to use it.

In the later models of the Fleuss, Draeger, and Westfalia, caps are provided to which the mouthpiece may be strapped when in use. With such straps properly adjusted there is comparatively little danger of the accidental dislodgment of the mouthpiece. The mouthpiece would, however, be even more secure if attached to a piece over the nose like the noseguard used by football players.

THE NOSE CLIP.

Although the present types of nose clip effectively compress the nostrils and may be worn with comparative comfort, they are easily displaced. In actual rescue operations it has repeatedly happened that they have been knocked off. If the wearer should fail to find and replace the nose clip immediately the results would be serious. Some means of holding the nose clip in position more securely are desirable.

SALIVA TRAPS.

One of the drawbacks of the mouthpiece is that it stimulates in many men a copious formation of saliva. This is liable to be discharged into the exhalation tube. In the Westfalia apparatus this feature is particularly annoying and adds to the fouling of the breathing bag. Some of the saliva may even be carried to the absorber, where it comes in contact with the alkali and causes heat. A saliva trap of at least 250 c. c. capacity should be attached to the metal mouthpiece on the Draeger and the Westfalia apparatus. That of the Fleuss apparatus should also be enlarged.

GOGGLES.

Various types of goggles have been tested and worn in irritating fumes and smoke. None of the foreign models have given satisfaction. The "Cover" and "Hayward" goggles have in general given satisfaction. Each of these types will fit a great variety of eyes and the method of preventing their fogging is simple. Surrounding the glass or mica on the inside of the frame is a cavity which will hold about 2 c. c. water, and does not allow it to spill when the goggles are in place. If the glass becomes fogged the head may be held forward until the plane of the glass is horizontal and a gyratory movement of the head causes the water to flush the inside of the glass and remove the fog.

UNIONS.

As regards joints and connections the Fleuss excels both the Draeger and the Westfalia. This is a decided advantage, as the risk of leakage is proportionally decreased. A single joint left insecure may cost the life of the wearer. The many connections and joints on the Draeger and the Westfalia apparatus require careful inspection to insure their being made fast. Screws having a cross arm for turning admit of making the joint reasonably tight, but thumbscrews with a circular milled head are not so reliable, as a heavy glancing blow will often loosen them. Such screws have frequently been found loose both in training and in actual rescue work. In many instances loosening has been due to the metal part of the tube not having a locked seat so that a slight movement of the metal part has worked the screw loose.

In the Draeger apparatus the valve below the absorber requires frequent inspection and cleaning. As now made the Draeger absorber goes into the apparatus either end up. As it absorbs better when used in one direction than in the other, it should be made so that it can go in only the right way. It would be convenient if the words "top" and "bottom" were stamped in the metal of the cartridge.

In the Fleuss the joint with which most trouble has been experienced is the connection between the saliva trap and the breathing bag. Frequently the men of a rescue crew, in assembling the apparatus, do not make this joint tight enough to resist a slight blow, and the union becomes loose.

There is always danger of losing oxygen if the union that attaches the reducing valve to the bottle is not turned tight. A hard blow on this valve, which is much exposed, especially in the Fleuss, may loosen the union and permit the oxygen to escape. Some device to lock the valve in position would correct this defect. In an English mine a man who was wearing a Fleuss apparatus lost his life because the main valve from his oxygen cylinder was turned off by being rubbed against the ground when he was crawling.

Also in the Draeger the main valve for shutting off the oxygen supply is in an exposed position where it is liable to blows as the wearer travels through restricted passageways. This valve, however, is strongly made and has withstood many hard knocks without injury. One of the engineers of the bureau, while combating a mine fire, happened to turn off this valve inadvertently while passing a hose line forward by catching it on the milling on the valve handle. Fortunately he was quick to discover the trouble and again opened the valve.

In the Westfalia apparatus the large absorber containing the alkali is carried so high upon the shoulders as to be liable to injury by striking the roof.

TUBES.

The connecting tubes of the Draeger apparatus are so exposed that they are sometimes mashed nearly flat by striking against the side walls in a mine. The tubes leading from the mouthpiece to the breathing bags of the Draeger, Fleuss, and Westfalia apparatus in the later models are similar in construction, being flexible corrugated and practically noncollapsible rubber of excellent quality, covered with cloth. It is important that the corrugated part should extend up close to the metal connection; otherwise the smooth end of the tube has a tendency to be closed by bending and may ultimately break. The metal-wound tubing in use in the earlier models of the Draeger and the Westfalia was a source of trouble, as the tubes were liable to collapse from a hard blow or if accidentally stepped on.

The method of attaching the tube to the metal ends is of much importance. To insure that the tube can not be accidentally pulled off in case it becomes caught on an obstruction it should be firmly held either by a clamp or by winding with wire. The metal end should slip inside the tube and have on its inner end a shoulder or rim over which the tube will not pass when the clamp or wire is in place. The tube should pass down as close to the wearer's neck or body as possible, so as not to be liable to be caught on obstructions.

PRESSURE GAGES.

In the Draeger and Fleuss apparatus the pressure gage is in front and can be seen by the wearer. In the Westfalia it is behind, so that the wearer can not see it himself and must depend upon a comrade to observe it for him. It is particularly important that the pressure gage should not give an erroneous indication of the supply of oxygen remaining in the tanks, as the wearer of the apparatus would thereby be misled as to the time he could safely continue in a dangerous atmosphere. In a period of two years, of 200 or more gages in the service of the bureau, about 10 per cent have been found to be out of order. It is especially important that the gage should register the lower pressures. All gages should be frequently tested in comparison with a standard and reliable instrument. The most reliable form of instrument for this purpose is one constructed of a heavy-walled glass tube bent in the form of a U, one limb of which is closed and contains air; the other is partly filled with mercury. The pressure is inversely proportional to the volume to which the air in the closed limb of the U tube is compressed.

REDUCING VALVES.

The reducing valve of the Fleuss apparatus seldom calls for repair, but the Draeger and the Westfalia require much attention to keep them in condition to deliver a constant volume of oxygen and also a constant circulation of air through the injector. The principal difficulty is due to the clogging of the opening in the nozzle, arising apparently from oxidation of the metal and corrosion of the end of the nozzle. The pilot within the chamber also becomes corroded and reduces the efficiency of the injector. In the Westfalia fine particles of alkali sometimes collect in the injector and restrict the passage of air and reduce the volume in circulation. Until the injector is discarded, as it should be, the valves should be frequently removed from the apparatus and the injector chamber examined and made clean. When a Draeger or a Westfalia valve becomes clogged in the nozzle, removal is necessary. This requires the services of a skilled mechanic or instrument maker.

The supply of oxygen through the reducing valves is controlled by a nozzle that has an aperture only 0.004 to 0.006 inch in diameter. The pressure behind the nozzle ranges from 50 to 110 pounds per square inch and furnishes 2 liters of oxygen per minute. The orifice is so exceedingly small that it furnishes practically the same weight of oxygen per minute at sea level as at an altitude of 10,000 feet, although at the latter elevation the volume will be greater because of the reduced atmospheric pressure. The large opening in the nozzle of the reducing valve of the Gibbs apparatus is one of its best features.

In determining the oxygen flow of any fixed-feed apparatus it is important to take into account that the density of the oxygen measured at the prevailing atmospheric pressure decreases in proportion as the barometer is below that of sea level. A quantity of oxygen which at atmospheric pressure and a temperature of 68° F. at sea level has a volume of 2 liters would expand to 2.41 liters at an elevation of 5,000 feet and to 3.03 liters at 10,000 feet.

RELIEF VALVES.

For the purpose of expelling from the breathing bag excess oxygen or air, each of the three types of apparatus now in general use in America is provided with a relief valve. Without such a valve the pressure within the apparatus would afford at times an uncomfortable resistance to the wearer's expiration.

On the Fleuss bag the valve is held closed by a spring and is opened by pressure with the finger. The valve is conveniently located but sometimes becomes corroded by the alkali in the bag. Wearers of the Fleuss apparatus are in the habit of opening this valve and squeezing the breathing bag, and then refilling the bag with fresh, cool oxygen by means of the by-pass on the tank. This proceeding is, however, wasteful of oxygen, and has only a momentary cooling effect, as the large mass of hot alkali immediately heats the fresh oxygen. There is also danger that if the wearer fails to remove his finger from the blow-off valve before ceasing to squeeze the bag the elasticity of the bag may draw in a considerable volume of deadly gases from outside. Any automatic relief valve should be set to open under a positive pressure of 8 or 10 centimeters water gage.

The relief valve in the Draeger and the Westfalia apparatus is held closed by means of a coiled spring adjusted to such a tension that a minimum pressure of 8 to 12 centimeters of water causes the valve to open. It is entirely automatic in its action and can not be operated by the finger. In different models of the Draeger and the Westfalia apparatus this valve is differently placed. It requires frequent inspection and cleaning, as otherwise it may fail to open under the pressure for which the tension is set. Failure to open when there is an excess of pressure in the bag causes the wearer some distress. By holding the breath and pressing the bag with the hand the valve may be forced to open, but too much pressure may burst it or make a leak in some part of the circulating system. The pressure required to open it should not be more than 8 or 10 centimeters water gage.

As a precaution against accumulation of nitrogen or hydrogen in the apparatus it is advisable also that a relief valve operated by the finger should afford a slight outward leak under even 0.5 centimeters water gage. Special provision for a slight outward leakage has been made in the Gibbs apparatus.

TESTS FOR PRESSURE AND VACUUM OR VOLUME OF CIRCULATION.

So long as injector types of apparatus with artificial circulation are in use it is important that the artificial circulation should be carefully tested in each apparatus before it is worn. With apparatus of this type in the service of the Bureau of Mines there were made during one month 280 separate tests on 71 Draeger apparatus, and 160 separate tests on 40 Westfalia apparatus, with the result that 4 Draeger and 3 Westfalia apparatus were found to be unsatisfactory as regards the readings of pressure and vacuum, which indicate the efficiency of the circulation afforded by the injector.

As already stated, artificial circulation by an injector is a feature that should be discarded entirely and replaced by natural circulation of air depending on the wearer's breathing.

FREEDOM OF MOVEMENT PERMITTED BY VARIOUS TYPES.

The Fleuss apparatus is well designed as regards the distribution of the weight on the body—the oxygen cylinders hanging in the small of the back and the bag containing the alkali in front—and is particularly well adapted for use in low and restricted passages. It surpasses in this respect both the Draeger and the Westfalia types. The time required for the wearer to extricate himself from the apparatus is, however, unnecessarily long. At least four buckles must be opened. Snap hooks, attached to adjustable straps, would be an improvement.

The Draeger apparatus places practically all of the weight upon the wearer's back. The supporting straps are narrow and become painful upon the shoulders. The absorber and oxygen bottle extend high on the back and make traveling under a low roof difficult.

The Westfalia apparatus, like the Draeger, places practically all of the weight upon the wearer's back. The shoulder straps are wider and padded, and do not pain the shoulders so much. The absorber and cooling tube are carried high on the back and, when worn without a protective shield, are liable to injury from a low roof. Both in actual rescue operations and in training the absorber has been broken in this way. A perforated metal shield may be obtained from the manufacturers that gives a large measure of protection to the exposed parts.

CARE OF RUBBER PARTS.

One of the most serious difficulties in the way of devising and constructing a reliable mine rescue apparatus is the necessity of using rubber. So-called pure gum rubber remains soft and elastic in Europe for months, but in the dry and brilliant climate in which most American mines are situated it becomes stiff and brittle in as many weeks, and in the elevated regions of the West in almost as many days. It appears at present impossible to avoid entirely the use of rubber, but it is evident that the parts composed of rubber should be as few as possible. The rubber used should be of the red variety and not the black pure gum frequently used in Europe, as the former outlasts the latter many times in the American climate. Pure gum rubber should be used for the mouthpiece however, as cases of lead or antimony poisoning are said to have occurred from chewing or sucking rubber containing these substances. As it appears that sunlight and lack of moisture are the principal causes for the deterioration of rubber, all of the rubber parts of rescue apparatus when not in use should be kept as far as possible in a moist place and in absolute darkness, and not in a hot, dry room.

BREATHING BAGS.

In the Fleuss apparatus the breathing bag is made of heavy rubber and serves to hold the caustic soda used for absorbing the exhaled carbon dioxide. When given the care recommended by the manufacturers these bags last for a number of months in daily use and retain their elasticity and flexibility for months when stored in cool and moist places. Lack of attention to the prompt removal of the soda remaining after use and failure to wash the bags out with hot (not boiling) water have been the principal causes of shortening the life of these bags.

Some of the bags when received from the factory have shown leakage where the rubber plugs are inserted to hold the nipples to which the breathing tubes are attached. The manufacturers can remedy this by properly testing the bags before they are shipped.

The Draeger and the Westfalia bags are constructed of vulcanized rubber-lined or rubber-treated cloth. They require special care to retain their flexibility; on long standing, especially in hot and dry climates, the rubber hardens and cracks when handled. At places where the atmosphere has a relatively high humidity the bags last well if frequently handled and rubbed, but if stored in a hot, dry room the rubber soon hardens and cracks on handling. When inspecting apparatus stored away for emergency use in mines, one of the authors has frequently found the bags of the Draeger and the Westfalia in a condition wholly unsatisfactory for service.

Leakage usually appears first at the outer seam, more especially in the Draeger bag, which has its support and attachments for holding the leather apron sewed and cemented into the seam of the bag. Recently at the suggestion of the Bureau of Mines these supports and attachments were arranged so as to be made an extension of the cloth out of which the bag is constructed.

DEODORIZING AND STERILIZING BREATHING APPARATUS.

For sanitary reasons any oxygen-breathing apparatus should be so constructed that all parts of its breathing circuit can be easily washed out and kept clean. The use of some disinfectant that will not be injurious to the metal or fabric of the apparatus is also desirable. Formalin appears to be best suited for this purpose, and should be used in a 5 per cent solution. Commercial formalin is a solution of about 40 per cent formaldehyde gas in water. The solution to be used may be made by adding one volume of formalin to 19 volumes of water.

At least once a week, while the apparatus is in service, the tubes and bags, the mouthpiece, its attached tubes, and the saliva trap should be washed, soaked in a 5 per cent formalin solution for one hour, then rinsed with clean water.

Of the three types mentioned the Fleuss apparatus lends itself most easily to cleaning, deodorizing, and sterilizing. The Westfalia bags and tubes are difficult to wash and sterilize, because of the difficulty in draining the bags. The Draeger bags and tubes are much more easily washed and sterilized than those of the Westfalia.

ABSORBERS FOR TRAINING PURPOSES.

When frequent practice is taken or when large numbers of men are being trained, the cost for Draeger and Westfalia cartridges and of alkali for the Fleuss becomes an item of importance.

For practice with the Westfalia, cartridges marked No. 11 are obtainable; a refillable cartridge is also furnished. Neither of these absorbers is intended for use in actual rescue work, and neither is of sufficient capacity to enable the performance of work called for in the regular schedule of training. The manufacturers of the Draeger apparatus furnish no cartridges designed for practice only. For the Fleuss apparatus in all mine-rescue work high-grade stick caustic soda should be used. It costs 15 to 20 cents per pound. For training and practice a less pure and much less expensive soda has been found by the bureau to meet the requirements satisfactorily. The "Giant" brand of lump caustic soda, costing 8 cents per pound, has been found by analysis to contain 90.09 per cent sodium hydroxide, 4.76 per cent sodium carbonate, and 5.15 per cent moisture and impurities. In a practice test with this material in the bag of the Fleuss apparatus air samples taken after 30, 60, 90, and 120 minutes, contained, respectively, 0.25, 0.24, 0.52, and 0.63 per cent of carbon dioxide.

LIMITATIONS OF RESCUE WORK WITH PRESENT TYPES OF APPARATUS.

When a miner puts on breathing apparatus he should know its limitations and should regulate his physical exertion to conform to them. Otherwise, as abundant experience has demonstrated, he may exert himself beyond the capacity of the apparatus and may soon be in serious trouble.

Experience has shown that if he walks too fast or works too hard he will need the assistance of his comrades in order to reach fresh air. It is important therefore that a rescue crew should not penetrate poisonous or irrespirable air to a greater distance than it would be possible for the crew to carry to safety one of its members.

The crew should be instructed always to work as a unit, the members to keep together, no one or even two men being allowed to lag or stray. One man in difficulty needs at least two others, and often four or more, to assist him effectively. Even when four members of a crew are carrying a disabled comrade, the work may be too strenuous and they may become dangerously distressed unless frequent rests are made.

The work of removing the dead from a mine after a disaster is beyond the limitations of the present types of breathing apparatus, and should not be attempted except for short distances and then only while the rescue crew is traveling slowly and resting at frequent intervals.

The pressure gages of all members of a crew should be read frequently and the lowest reading should govern the crew's stay in irrespirable air.

The men should be trained to exercise great care while crawling through low passages lest the breathing bags be pressed flat and the air expelled. All apparatus of the fixed-feed type should be fitted with a by-pass valve that can be easily reached with the hand, and the men should be trained so that they will use it instinctively for refilling the bag in case it is compressed and emptied.

In mines having passageways high enough to permit walking erect, a rescue crew may not safely penetrate more than 2,000 feet from fresh air; in low and restricted passages the distance should be much less, depending upon the nature of the obstructions encountered. For a height of 4 feet 500 feet may be considered a maximum. In mines having a roof less than 4 feet high the rescuers are compelled to crawl and should one of the crew meet with accident or become distressed, assisting him to fresh air is very difficult. Under such conditions 200 to 300 feet may be considered the maximum distance beyond fresh air to which the crew should attempt to penetrate.

It does not necessarily follow from the foregoing statements that breathing apparatus may not be used to great advantage after explosions or mine fires. For building stoppings, bulkheads, and dams, apparatus has been used in many mines to great advantage. There need not be any excessive danger provided the men do not attempt to travel too fast or to exert themselves in working beyond the limitations of the apparatus. Courage and the desire to save life should not be allowed to lead the wearers of rescue apparatus beyond these limitations. In the great majority of instances a contravention of this rule merely adds to the loss of life.

METHODS OF DETERMINING THE FITNESS OF A MAN TO WEAR APPARATUS.

In the foregoing attention has been fixed on the reliability of the apparatus. Evidently it is no less important that the wearers should be strong, healthy men. The wearing of breathing apparatus of any type is in itself equivalent to considerable physical exertion. In actual mine rescue work extreme demands on physical vigor are almost certain to occur. Every man who is to take part in such work should have been subjected to a thorough medical examination, particularly as regards his heart, arteries, and kidneys. In general he should be under 40 years of age, of good muscular development, accustomed to hard work, rather under than over the average weight for his height, and never fat. His arterial pressure when resting should not be more than 140 mm. of mercury.

He should also be subjected to a number of tests in regard to his capacity for vigorous exertion. Running up and down a flight of stairs 5 or 10 times as rapidly as possible, with a total climb of 60 to 100 feet, is perhaps as good a test as any. The pulse rate, condition of breathing, and arterial pressure should be observed before the test, immediately at the end of this exertion, every 5 minutes for 20 minutes thereafter, and finally an hour later. It is probable that the arterial pressure is the least significant of the three methods of observation. In a healthy man it may be raised 30 or 40 mm. above the resting value for the individual. The pulse may be accelerated to more than double the resting rate; and the rate of breathing may be increased to the point of vigorous panting.

The main distinction between a vigorous man and one who is unfit for mine rescue work is in the character of the recovery from these conditions. The weak man or one unfit for vigorous exertion may in some cases faint or turn sick. In general, however, such a man differs from one fit for vigorous exertion in that his arterial pressure may rise little if at all, but the pulse continues greatly accelerated, and the breathlessness lasts for many minutes after the exertion, whereas the vigorous man's arterial pressure, pulse, and respiration are considerably augmented, but rapidly return to their normal condition. Even within the first 5 minutes after the cessation of the effort the pulse should fall approximately halfway to its normal rate again, and the respiration should so far have recovered that the man may speak easily. An hour later the pulse should be only a few beats to the minute above the initial count. After such a test a vigorous man should experience or exhibit neither immediately nor later any feeling of discomfort or trembling of the limbs. In addition to such a test as this, a man to be safe in rescue apparatus should be able to travel at least 10 minutes at the rate of 5 miles an hour, while wearing the apparatus under full service conditions, without getting greatly out of breath.

It is probable that the factor which more than any other determines the capacity of a man to make and to withstand physical exertion is the functional power of the heart. As an indication of this, however, the breathing is a more reliable index than either arterial pressure or the pulse. The pulse rate in one healthy man at rest may vary widely from that in another man; neither 50 nor 90 beats per minute is in itself abnormal. It is probable that a man may be perfectly healthy with an arterial pressure of 100 or of nearly 140 mm. of mercury. Furthermore a heart may be perfectly capable of supplying all the ordinary needs of resting conditions and of moderate activity, and yet during vigorous exertion it may be incapable of meeting the full demands. In the latter case the deficient circulation is more evident by the violent breathing and prolonged subsequent breathlessness (or as expressed scientifically by the high respiratory quotient) than by any other symptom. This is due to the fact that the breathing is controlled from the respiratory center in the brain, which is very sensitive to the character and amount of the blood pumped to it by the heart. Although it is difficult to draw up rules regarding the matter, a little experience in observing men under severe muscular tests enables the observer, who fixes his attention upon the breathing, to test more effectively than in any other way whether or not the exertion is really beyond the subject's capacity.

SOME CHARACTERISTICS OF ASPHYXIATING GASES IN RELATION TO BREATHING APPARATUS.

It is outside the scope of this paper to consider in detail the physiological effects of the various harmful gases that men sometimes inhale, but certain considerations regarding the special arrangements of breathing apparatus to be worn as a protection against the principal types of such gases are included here.

Physiologically harmful gases fall under four classes:

1. Gases that are simply the gaseous forms of substances, which, without being especially irritating to the lungs, may be absorbed from the breath, and, after being carried by the blood to all parts of the body, act as general or protoplasmic poisons. Examples of such gases are arsenurated hydrogen and hydrocyanic acid. Such gases are not for the most part of special interest in relation to breathing apparatus.

2. Gases that are so intensely irritant to the bronchial tubes and lungs that death may follow the injuries to these organs alone. To this class belong sulphur dioxide, bromine, and chlorine. The principal constituent of the asphyxiating gas that has been used recently in war seems to be chlorine. Against such gases a considerable degree of protection is afforded by a simple respirator composed of a sponge or of several layers of loosely woven cloth wetted with some absorbent chemical, for instance sodium hypochlorite, and held against the nose and mouth. The only example of such gases that occurs with any frequency in mines is the higher oxides of nitrogen set free when dynamite burns without exploding. Such dynamite fumes are peculiar in that, when they are considerably diluted with air, their immediate irritant effect is comparatively slight. Thus men may work for some time while inhaling them and may then emerge unaware of injury. A few hours later the condition of the lungs becomes acute and terminates in the peculiarly agonizing death characteristic of this class of gases.

3. Gases that are physiologically inert and which induce asphyxia merely because an insufficient amount of oxygen is mixed with them. Such gases are nitrogen, which with more or less carbon dioxide constitutes "black damp," hydrogen, and methane or "fire damp." The immediate physiological effects of insufficient oxygen have been described in previous pages. There are strong theoretical grounds for expecting that a man who has suffered prolonged, but at the same time incomplete, asphyxia of this sort will subsequently exhibit

symptoms practically identical with those induced by carbon monoxide. A case of this sort has in fact recently been reported.[a]

4. Carbon monoxide. This deadly gas, the product of incomplete combustion, is responsible for more deaths than all other gases combined. It is mainly as a defense against carbon monoxide that rescue apparatus is used. To it are chiefly due the poisonous effects of smoke in burning buildings, fumes around furnaces, illuminating gas, and the afterdamp of explosions of methane and coal dust in mines. It is odorless, or almost so, and has no irritant effect, either immediately or subsequently upon the lungs. It appears to be physiologically an entirely inert and harmless gas except in a single respect, its avidity for hæmoglobin, the red coloring matter of the blood. With this substance it combines in exactly the same way as does oxygen, but with an attraction approximately 250 times as strong.

As physicians whose education has not included the modern science of physical chemistry hold in general a quite erroneous conception of this matter, a few words of explanation regarding it may be given here.[b]

When a few drops of blood diluted with water, so that changes of color are easily perceptible, are exposed to the air by shaking in a glass vessel, the hæmoglobin unites with oxygen. If it is then exposed to an atmosphere containing less than 8 or 10 per cent of oxygen, the color changes from red or pink to a purplish tint, owing to the separation of a part of the oxygen from the hæmoglobin. This combination and separation are essentially the processes occurring normally in the lungs and in the working tissues of the body as the blood circulates through them.

If the diluted blood is exposed to illuminating gas it quickly assumes a cherry-red color, characteristic of carbon monoxide saturated hæmoglobin. It is almost as easy, although a somewhat slower process, to remove the carbon monoxide as it is to infuse it. It is merely necessary to shake the fluid thoroughly with air. In other words, the union of carbon monoxide and hæmoglobin is not a permanent combination, but depends on the opposed mass actions of the oxygen and of the carbon monoxide present.

TEST FOR CARBON MONOXIDE POISONING.

Owing to the facts that the affinity of carbon monoxide for hæmoglobin is 250 times as strong as that of oxygen, and that air contains about 21 per cent of oxygen, it follows that blood which is

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[a] Loyd, W. D., The use of rescue apparatus at large mill collieries, Hudders Field: Coll. Guard, vol. 106, Nov. 7, 1913, p. 957.

[b] See Henderson, Yandell, Carbon monoxide poisoning: Jour. Am. Med. Assn., vol. 67, August, 1916, pp. 580–583.

fully exposed to an atmosphere of air containing one three-hundredth of 21 per cent, or 0.07 of 1 per cent, of carbon monoxide will come into a condition in which half the hæmoglobin will be combined with oxygen and half with carbon monoxide.

Accordingly when a man breathes an atmosphere containing even a trace of carbon monoxide his blood in time becomes partly saturated with this gas, the extent of saturation depending on the relative amounts of carbon monoxide and oxygen present, multiplied by the affinities of these gases for hæmoglobin. The rate at which the saturation proceeds depends upon the amount of breathing.

In a man at rest the tissues consume little more than one-third of the oxygen that the blood brings to them, whereas during muscular exertion nearly two-thirds is utilized. Accordingly the blood of a man at rest may become nearly one-third saturated with carbon monoxide without his realizing that anything is wrong. If, however, he tries to make any considerable exertion the fraction of his hæmoglobin uncombined with carbon monoxide is insufficient to transport the oxygen needed, and he may collapse. When his blood is more than half saturated he is liable to collapse even at rest. If he remains for a considerable time in this condition the delicate nerve cells of the brain, and less often other organs also, are injured by the continued lack of oxygen, and unconsciousness (coma) results. As a rough estimate it may be stated that a man who has breathed air containing 0.2 per cent carbon monoxide for four or five hours or 0.4 per cent for one hour will die. In air containing 2 to 5 per cent of carbon monoxide, as after an explosion of coal dust, nearly all of the hæmoglobin is combined by the first few breaths drawn, and death follows almost as quickly as in drowning.

The principal bearing of these facts to be emphasized here is the imperative need for breathing apparatus that can not easily be knocked off (as the nose clip not infrequently is) and allows no inward leakage.

These facts also show how important it is to carry a man overcome by carbon monoxide into fresh air and remove his apparatus as soon as possible. For 15 to 20 minutes thereafter it is beneficial to administer pure oxygen or air considerably enriched with oxygen by means of a tank, bag, and mask with valves that do not allow rebreathing. If the victim, though unconscious, is breathing in nearly the normal manner, he may be allowed to inspire the oxygen himself. If the breathing is slow and irregular, or has stopped entirely, as may be the case in sudden exposure to concentrated carbon monoxide, artificial respiration by the Schaefer method, but with administration of oxygen, should be performed.[a] The stronger the oxygen the sooner

[a] Cannon, W. B., Crile, G. W., Erlanger, Joseph, Henderson, Yandell, and Meltzer, S. J., Report of the committee on resuscitation from mine gases: Tech. Paper 77, 1914, pp. 10, 15–17.

the carbon monoxide is displaced and the oxygen-carrying capacity of the hæmoglobin restored. Even when only pure air is breathed the mass action of its oxygen is usually sufficient to displace the greater part of the carbon monoxide in an hour or even only half an hour, so that the oxygen-carrying power of the hæmoglobin is restored sufficiently to meet the patient's needs. Practically all of the carbon monoxide is eliminated and the hæmoglobin fully restored in three or four hours. This is facilitated by the rapid breathing, usually 30 to 45 times per minute, which such cases exhibit during recovery and which is probably caused by incomplete combustion products formed in the tissues during the asphyxia and circulating in the blood for some hours thereafter, or by some long lasting effect on the respiratory center.

In many instances the victim never recovers consciousness and dies a day or two later. Many physicians still hold to the belief (now completely disproved) that the prolonged coma is due to retention of the carbon monoxide, and advocate bleeding, infusion of oxygenated saline solution, transfusion of blood from some healthy person, and other active efforts at restoration. None of these procedures nor any known procedure aside from careful nursing and symptomatic treatment has been demonstrated in practice to be of any benefit. Recovery when it occurs is not due to them, but in spite of them. There is indeed no reason to expect them to be beneficial, for it is not retention of carbon monoxide but the results of the injury to the brain and other organs, caused by lack of oxygen supplied by the blood while the patient was breathing the gas, which is responsible for the prolonged coma and subsequent death or incomplete recovery. There is no known method of restoring tissues to normality after parenchymatous degenerations have once been initiated. Left to itself nature does all that can be done to stop the abnormal processes. The man recovers completely if the asphyxia has not been too intense and prolonged, although in many cases men who have once been "gassed" exhibit a muscular weakness of the heart permanently thereafter. More severe cases recover only with the loss, partial or complete, of vision, power of speech, or with some other nervous defect.

The foregoing statements regarding the effects of carbon monoxide upon men are based principally upon the work of Dr. Haldane.[a]

[a] Haldane, J. S., The relation of the action of carbonic oxide to oxygen tension: Jour. Physiology, vol. 18, 1895, pp. 200–217; The action of carbonic oxide on man: Jour. Physiology, vol. 18, 1895, pp. 430–462; A method of detecting and estimating carbonic oxide in air: Jour. Physiology, vol. 18, 1895, pp. 463–469. For a summary of Dr. Haldane's observations, both on the scientific side in the laboratory and in practical work after mine explosions in England, see Report to the Secretary of State for the Home Department on the causes of death in colliery explosions and underground fires, London, 1896.

The experience of the authors has confirmed them in every detail. Thus one of the authors has repeatedly in experimental work breathed air containing carbon monoxide until his blood was 20 per cent saturated. No vigorous exertion was made and no ill effects were experienced. Within two or three hours practically all of the carbon monoxide had been eliminated and he was as fit for vigorous exertion as before. This of course would not have been the case if any lasting deterioration in the hæmoglobin of the blood had been produced. Furthermore one of the authors has repeatedly examined the blood of persons overcome by illuminating gas in accidents at New Haven, Conn. In six successive cases in which a sample of blood was taken and examined not more than two hours after the patient had been removed to fresh air from the room in which asphyxia had occurred, the elimination of carbon monoxide was found to have been so rapid that in only a single case was the presence of a small amount in the blood still demonstrable. In all of these cases the blood had undoubtedly been saturated beyond the danger point of 60 per cent, yet two hours in fresh air had served to reduce the carbon monoxide to less than 15 per cent, the amount which the small pocket spectroscope employed was capable of distinguishing. Four of these cases died within 24 to 60 hours after the asphyxiation. One, which oddly enough was the case above noted in which a small percentage of carbon monoxide was detected two hours after removal to fresh air, recovered completely. Another still exhibited profound nervous impairment a month later.

These observations are sufficient to demonstrate the unwisdom of bleeding patients who have been poisoned with carbon monoxide, in order to stimulate the formation of new red blood cells. Such a formation requires several days to become fully effective. In the majority of cases the patient's blood is practically free from carbon monoxide before the bleeding is performed. Cases of carbon-monoxide poisoning exhibit such wide variations in the severeness of the initial symptoms, in the length of time required for recovery, and in the completeness of restoration, that it is difficult to establish conclusions regarding them from merely clinical or statistical evidence. Theoretically there is no treatment that would seem more likely to diminish a patient's chance of recovery than treatment by bleeding.

The experience of one of the authors supplies the following cases: Three men, all Filipinos of approximately the same age, weight, and physique, were overcome by illuminating gas while sleeping in a room together. One was treated during the following day by withdrawing blood and injecting saline solution saturated with oxygen. For a second, a transfusion of blood from another and unpoisoned Filipino was performed. For the third, nothing was done beyond the ordinary procedures of good nursing. The first two died in the course of the two or three days following the asphyxiation. The third survived, but when seen three weeks later, had recovered only sufficiently to answer the simplest questions regarding his name and where he came from.

Thus it appears that about all that can be done for cases of carbon monoxide poisoning is to administer artificial respiration when the person's own breathing has failed or is feeble, to administer oxygen for not more than half an hour, to keep them warm if the temperature has fallen, to supply water to the system, preferably by a Murphy drip, and otherwise to give them good nursing and such symptomatic treatment as may be called for. Anything beyond this is more likely to do harm than good.

WHEN AND HOW TO USE RESUSCITATION APPARATUS.

The subject of resuscitation, both by manual methods and by means of apparatus, has been fully dealt with in Technical Paper 77,[a] which presents a report based on the investigations of a commission of physiologists, of which one of the authors was a member. The general topic therefore need not here be dealt with. As there is, however, apparently a widespread misapprehension both among laymen and physicians regarding what can and what can not reasonably be expected of resuscitation apparatus, and particularly of devices for supplying artificial respiration, a few words on this subject are in point.[b]

It is quite useless and may indeed be harmful to administer artificial respiration either by manual methods or with an apparatus to a patient who is himself breathing effectively. This would appear to be self-evident, were it not for the fact that "cures" by means of the various devices for artificial respiration now on the market have been repeatedly claimed, both by the manufacturers and by the physicians in attendance, although the patient was merely unconscious, and is admitted to have been at all times breathing vigorously of his own accord. No mechanical device constructed by man is as well adjusted to supply the patient's breathing as are his own respiratory organs.

The field of usefulness for apparatus to supply artificial respiration is limited to those cases in which spontaneous respiration has stopped or has become extremely feeble or irregular. Well-founded scientific evidence indicates that the heart will be asphyxiated and

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[a] Cannon, W. B., Crile, G. W., Erlanger, Joseph, Henderson, Yandell, and Meltzer, S. J., Report of the committee on resuscitation from mine gases: Tech. Paper 77, Bureau of Mines, 1914, 36 pp.

[b] For a fuller statement of the advantages and disadvantages of such devices see Henderson, Yandell, Resuscitation apparatus: Jour. Am. Med. Assn., vol. 67, July 1, 1916, pp. 1–5.

stop beating within 8 minutes or at most 10 after oxygen ceases to be absorbed from the air of the lungs into the blood. Unless therefore artificial respiration either by manual methods or with an apparatus is supplied to a patient within this period after he has stopped breathing, there is practically no use in administering it at all. It is true that a somewhat larger volume of artificial respiration can be supplied with some of the devices now on the market than with the prone pressure or Schaefer method recommended by the bureau. The disadvantage of all apparatus, however, is that knowing that it is available, persons who might otherwise administer artificial respiration by manual methods immediately, are liable to wait until the apparatus can be brought, or to try to carry the victim to it, and thus to neglect to utilize the one chance of restoring the victim. Even when apparatus is on the spot the time spent in adjusting it on the patient can be more profitably used in immediately applying artificial respiration by the manual method. In the few seconds lost in adjusting the apparatus the patient's heart may stop beating. No form of artificial respiration will set the heart beating again after it has once stopped entirely.

The essential feature of all such apparatus is merely some source of interrupted air current, such as a simple hand or foot bellows, a bicycle or automobile tire pump, or a tank of compressed air or oxygen, so arranged that fresh air is blown into the lungs and then withdrawn or allowed to escape 12 or 15 times a minute. This allows oxygen to diffuse into, and carbon dioxide out of, the blood.

In principle no apparatus yet devised, or that seems likely to be devised, accomplishes anything more than is afforded by the prone pressure method of manual artificial respiration. All claims regarding the advantages of "automatic action," "forcing oxygen into the blood," "sucking the poisonous gases out," etc., are merely impositions on the credulity of the purchaser.

In any form of artificial respiration it is essential merely that there should be no mechanical obstruction—as by false teeth, tobacco, or the tongue falling back into the throat—that the pressure under which the air is injected should be not more than just enough to cause a moderate inspiration, and that if any suction at all is used to aid the elastic recoil of the chest in expiration it should be of very slight force. Any large positive pressure and particularly a considerable negative pressure may injure the patient.

On the authors' recommendation, based on experimental examination of many forms of apparatus and on practical experience, the Bureau of Mines has removed all artificial respiration devices from its rescue cars, retaining only oxygen inhalers—oxygen tank, rubber bag, and mask with valves. For first-aid purposes the rescue crews are instructed to use the manual method of artificial respiration, supplemented, when the patient has been in poisonous gases, by oxygen inhalation. A clear case of life saving by the manual method was recently effected by one of the rescue men of the Bureau of Mines.

After careful consideration of the results, both of experiments and of practical experience, the authors make the following recommendations:

1. Apparatus in which a pump is used to force air into the lungs should have a blow-off valve, or equivalent device, set at 25 centimeters water gage. If the apparatus includes a pump to withdraw air from the lungs, there shall also be an inlet valve set at a negative pressure of 15 centimeters. These valves are best placed on the mask.

2. In apparatus in which reliance is placed on a tank of oxygen or compressed air, and in which the movements of respiration are controlled by a valve worked by hand alternately to inject and aspirate air, there should be safety valves, one set at a positive pressure of 15 centimeters and one at a negative pressure of 10 centimeters.

Lower pressures are recommended as limits for this type than for the pump type of apparatus, because the duration of each inspiration and expiration is not limited in the injector and aspirator devices as it is in the pump type by the plunger reaching the end of the stroke.

Devices for inducing artificial respiration are being extensively sold. For places where such apparatus can be immediately utilized when an accident occurs it may be the means of saving life. Thus, in the surgical operating room, at electric-power stations, at gas works, swimming pools and bathing beaches, in the work of a city fire department, and in mine rescue operations the apparatus may be kept at, or taken beforehand to, the spot where an accident is expected, and may be immediately used on any person who has ceased to breathe spontaneously. On the other hand, there is a wide field in which accidents occur and in which it is impossible to have the apparatus on hand. This is particularly the case in regard to electric shock in telephone line work, and in mining, and in most cases of drowning. Delay in the administration of artificial respiration by manual methods in such cases, in order to send for an apparatus, is particularly to be deplored.

Experience indicates that the knowledge that apparatus is available and "has been sent for" leads to such delay. Thus recently in an accident in which a large number of people were drowned, the victims, after having been taken from the water, were carried (so the authors are informed) some distance to a temporary hospital and treated with apparatus which was "rushed" to the spot. Naturally, not a single one was thus revived.

All apparatus of this sort should have stamped upon the case containing the machine the words "If spontaneous breathing has ceased, and the apparatus is not already on the spot, administer artificial respiration by manual methods without the loss of a moment, and continue to do so until the apparatus is brought; otherwise life will be extinct before the apparatus arrives. Except to remove the patient from a locality containing poisonous gases, never carry him to the apparatus. He will probably be dead before he gets there." This statement should be followed by the directions for the prone-pressure method of artificial respiration by manual means drawn up for the Bureau of Mines by the committee of physiologists above referred to. Every miner should learn the prone-pressure manual method. This is much more important than any purchase of existing apparatus for artificial respiration or the devising of new forms. The value of the prone-pressure method has recently been strikingly exemplified by a resuscitation effected by an employee of the Bureau of Mines.

Quite apart from the matter of artificial respiration is that of oxygen inhalation. The use of oxygen is very important, provided that it is applied immediately, for men unconscious from gas or smoke. As stated in the discussion of asphyxiating gases, it requires merely a tank of compressed oxygen from which the flow is controlled by hand, a rubber bag with a capacity of 10 liters or more, and a mask with an inspiratory valve connected with the bag and an expiratory valve to the outside air. Such apparatus should be much more generally provided and used than it is at present in connection with mines, gas works, and city fire departments. It may advantageously be used in connection with artificial respiration by the manual method.

Apparatus of this sort[a] is sold by most of the manufacturers of mine rescue apparatus. It is also easily put together in any city where tanks of oxygen are obtainable from stores carrying medical supplies and where bags and masks are obtainable from a rubber shop.

SOME ACCOMPLISHMENTS OF BUREAU OF MINES RESCUE CORPS.

In spite of its defects, the introduction of mine rescue apparatus in the United States has been directly and indirectly responsible for the saving of many lives. That there has not been a greater saving of life is due to two principal causes: (1) The absence of trained men and of apparatus immediately following a disaster, and (2) the limitations of present types of breathing apparatus, restricting the distance men may travel with safety and the time that they may work in poisonous or irrespirable gases.

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[a] Illustrations and descriptions may be obtained by application to the Director, Bureau of Mines.

The entire Bureau of Mines rescue corps has never consisted of more than 30 men, who are scattered throughout the mining districts of the United States. An idea of the dangers faced and the difficulties overcome in conducting rescue operations may be gained from the fact that in the past five years four men of this corps have lost their lives while wearing apparatus. The ratio of accidents is not so great when it is considered that the bureau rescue corps have taken part in a large number of mine recovery operations. Among the accidents at which rescue crews for the Bureau of Mines have rendered efficient service the following are particularly noteworthy:

In November, 1909, at the Cherry mine fire, Cherry, Ill., in which about 256 men were lost, apparatus men of the Bureau of Mines made the first descents into the sealed mine and recommended that the seals be removed and ventilation restored. Subsequently, with volunteer wearers of rescue apparatus, they assisted through an unventilated zone in the rescue of 21 miners who had barricaded themselves in a side entry for seven days.

In December, 1911, after a mine explosion at Briceville, Tenn., a bureau apparatus crew rescued three miners who had been barricaded in a side entry for two and one-half days. These three men and two others were the only survivors among 89 men in the mine when the explosion occurred.

The rescue crews of the bureau, in conjunction with local rescue volunteers, have also been instrumental in the saving of life at more than a score of other disasters.

During the seven-year period from January 1, 1908, to January 1, 1915, the bureau rescue men had attended a total of 283 mine disasters, in which 2,700 lives were lost; rescue apparatus was worn by 699 men, 92 miners were saved by apparatus men in the service of the bureau, 768 were saved by other rescuers, and 1,426 miners escaped unassisted. A summary of these facts is given in Table 11.

TABLE 11.—*Statistics of mine accidents attended by Bureau of Mines representatives from January 1, 1908, to January 1, 1915.*

Year.	Number of accidents attended.	Number killed.	Number wearing apparatus.	Number rescued by bureau rescuers and methods.	Number rescued by others.
1908	34	186	40	3	87
1909	7	321	20	28	53
1910	25	522	44	20	243
1911	36	462	110	13	81
1912	49	264	89	8	94
1913	80	598	243	19	198
1914	52	347	153	1	12
Total	283	2,700	699	92	768

From this table it will be seen that the efforts of the Bureau of Mines to induce mine owners to purchase and have on hand rescue apparatus have been attended with a large measure of success, and that even with the present defective types of apparatus the result has been a considerable saving of life, not only by the rescue crews of the bureau, but also by men trained under the direction of the bureau but in the employ of the separate mines.

THE ROLL OF HONOR.

Four men have lost their lives while wearing apparatus in the service of the bureau, J. E. Evans, John Farrell, Edward Evans, and Lewis M. Jones. Briefly, the circumstances of their deaths were as follows:

DEATH OF J. E. EVANS AT PANCOAST MINE.

On April 7, 1911, J. E. Evans, foreman miner of the Bureau of Mines, was overcome while endeavoring to rescue miners imprisoned by a fire in the Pancoast mine, Scranton, Pa. The fire area entered by Evans contained gases from the fire, the air being low in oxygen and high in carbon dioxide, with some carbon monoxide. Evans traveled 600 feet and complained of not feeling well. He stopped to rest and partly recovered, then started on again, and again complained. He tried to return with a companion, but after proceeding a short distance, staggered and fell. His apparatus was on when he died and seemed to be in good condition. Death was probably due to leakage of carbon monoxide into his helmet. When tested, it showed a flow of 2 liters of oxygen per minute, a pressure and vacuum of 10 cm. produced by the injector, and 70 liters of air in circulation. As the rescuing party of four had not traveled faster than 3 miles an hour, the quantity of oxygen should have been sufficient.

For one-half hour previous to putting on the apparatus Evans had been breathing the mine gases from the fire. Another man who had been subjected to the same gases was temporarily overcome.

DEATH OF JOHN FARRELL AT CHERRY VALLEY MINE.

On January 19, 1912, John Farrell, first-aid miner of the Bureau of Mines, was killed while exploring a fire area at the Cherry Valley mine, Cherry Valley, Pa. Analysis of the air in the area at the time showed 2.9 per cent oxygen, 42.08 per cent nitrogen, 50.88 per cent methane, 0.35 per cent carbon monoxide, and 3.79 per cent carbon dioxide. Farrell, while wearing helmet-type apparatus entered a room alone to look for a comrade who had disappeared in the dark. He was found with his helmet off, but death was considered to be due to carbon monoxide poisoning due to leakage of his apparatus, caused by a break in the cooler.

DEATH OF EDWARD EVANS AT ROCK SPRINGS, WYO.

The death of Edward Evans, foreman miner of the Bureau of Mines, during a practice trip in an unoperated mine on September

30, 1914, was probably caused by lack of oxygen or by heart failure induced by high elevation and lack of oxygen. Having traveled at the rate of 2 miles an hour for 30 minutes, he asked his four companions if they felt all right. Upon receiving an affirmative answer from each, he stated that they would all proceed to the outside. He stopped long enough to take chalk and mark on the rib of the coal the date, the name of his crew, and his initials (September 30, Crew C, E. E.). After having gone 25 feet he called to his crew that he must get out at once, and started to run. The four men ran after him and in about 100 feet caught him, and two of them each took hold of an arm and endeavored to assist him. He pulled off his nose clip and tried to take out his mouth breather. The two attendants restrained him from taking out the mouthpiece and one put his nose clip back on. He began to stagger. The attendants supported and helped him along until he finally became limp, after which the members of the crew carried him to the slope, where all but one became exhausted. While the one man of the crew not exhausted went to the base for the assistance of the reserve crew, which was ready for action, each sitting with his apparatus on ready to turn on oxygen, the other three men of the crew remained with Evans. In 15 minutes from the time of his first alarm he was brought to fresh air, but life was extinct.

While first-aid men and physicians were endeavoring to resuscitate Evans, the apparatus worn by him was taken out of the mine and tested immediately, and worn in fresh air and smoke fumes for 30 minutes, there having been a 30-minute supply of oxygen still remaining in the apparatus when taken off of Evans. The apparatus responded to all the tests for volume, pressure, vacuum, and quantity of air in circulation, and was worn 30 minutes by a man who walked 3 miles an hour without any discomfort.

On a previous trip in the mine Evans had taken a sample of the mine air on the second level in the second blind off the last room. A sample had previously been taken on the sixth level in the vicinity where Evans was overcome. The results of analysis of the two samples follow:

Results of analysis of mine-air samples taken previously to death of Edward Evans.

	Sample from—	
	Second level.	Sixth level.
Carbon dioxide (CO_2) per cent	4.93	6.01
Oxygen (O_2) do	14.99	15.72
Carbon monoxide (CO) do	0.00	0.00
Methane (CH_4) do	0.01	0.01
Nitrogen (N_2) do	80.07	78.26

DEATH OF LEWIS M. JONES AT BARRACKVILLE, W. VA.

Lewis M. Jones, mining engineer in charge of coal-mine investigations, had been for some time before his death entrusted with the investigation of the conditions causing explosions in mines and the effectiveness of the various methods of prevention. He had gone to the Jamison Coal & Coke Co.'s mine No. 7 at Barrackville, W. Va., to investigate an explosion which had occurred a few days previously. Although not serving regularly with the mine rescue crew he accompanied a party in an exploration of the mine on October 20, 1916. The party, consisting of five men, including Jones, had gone in about 2,900 feet when they stopped and examined the condition of their apparatus. The apparatus was apparently in good order, and thinking it possible that there might be some unrescued miners farther on, the party proceeded, Jones being the last in line. The party had gone only a short distance when it was noticed that Jones had fallen behind. On returning they found him leaning against the rib, and one member of the party caught him as he fell. Considerable time elapsed before he could be brough to fresh air. Although both breathing and heart beat had then ceased, artificial respiration was applied for some time, but without effect. Subsequent examination of the apparatus that he had been wearing disclosed a crack in the side of the rubber mouthpiece which, when first noted, was almost invisible when the rubber was not under any strain, but afforded a distinct leak when it was in the mouth. Death was possibly due to the cumulative effect of carbon monoxide drawn into the apparatus through the crack. It is possible that the crack developed after the inspection of the apparatus made by the rescue man before putting it on, and as a consequence of the handling incidental to recovering the body and pulling out the mouthpiece.

RECOMMENDATIONS FOR IMPROVEMENTS IN APPARATUS.

The general requirements which breathing apparatus should meet have already been stated (pp. 23–24). Any apparatus that can be devised is necessarily the result of compromise as regards many conflicting advantages and disadvantages, such as the weight, the amount of oxygen carried, the capacity to absorb carbon dioxide, the arrangement of parts, durability, and liability to breakage. Inventive skill, the judgment of practical mining men, and consideration for the physiological requirements of the wearer must all contribute toward improving the present types and devising new forms of breathing apparatus. The final decision as to what is best can be obtained only from future experiment and experience in actual work.

In general, however, the new apparatus devised for the Bureau of Mines by Mr. Gibbs embodies not only his skill in such mechanical details as the reducing valve, but the conceptions of one of the authors, who is a physiologist, of a man's respiratory requirements, and also the practical experience of the other author, who has supervised and directed and himself taken part in a great many recovery operations after mine disasters and fires. Nevertheless it must be frankly admitted that in attempting to attain what have seemed the vital needs, other features have had to be subordinated. Doubtless it will be found that in some respects the compromise adopted is not altogether the best. For example, all of the weight is placed upon the back, and the apparatus, although lighter than the Fleuss, does not hang as comfortably when the wearer is standing erect (which a man rarely does in actual rescue operations) as does the Fleuss. Experience alone can decide whether the gain in compactness justifies the arrangement adopted.

What is desirable in the way of change in the forms of apparatus hitherto in use is not that they should be made all alike, but rather that each should retain those features in which it excels and should be improved in those in which it is defective. To this end the following recommendations are offered:

1. The helmet of the type used with the Draeger and the Westfalia apparatus should be entirely discarded. Any device of this type which may be invented in the future should have a dead space of not over 200 c. c. and should be tested with the utmost care as to its tightness upon the face.

2. A self-adjusting oxygen feed valve should replace the fixed-feed valve now used. Whenever the fixed feed valve is used it should be set to a flow of not less than 3,000 c. c. as a minimum per minute, measured at a temperature of 60° F. and a barometric pressure of 30 inches of mercury.

3. The arrangement for artificial circulation in the Draeger and the Westfalia apparatus should be eliminated and replaced by a natural circulation. When the Draeger and Westfalia are used in their present forms the automatic circulation should be not less than 75 liters per minute. The injector should be placed between the exhalation bag and the absorber so as to decrease to the smallest possible limits the area in which a negative pressure occurs.

4. The weight of the entire apparatus should not be in excess of 35 pounds.

5. The absorption of carbon dioxide should be so nearly complete that the air in the circulation system during moderate exercise will not contain more than 0.5 per cent of carbon dioxide, and at no time, even during the most vigorous exercise, more than 1 per cent. The absorber should be capable of fixing at least 2.5 liters of carbon dioxide per minute.

6. A by-pass valve should be made a part of the apparatus, to be used in case of failure of the reducing valve, for refilling the breathing bag in case it is pressed flat, and for renewing the air contained in it in the event of poor absorption of carbon dioxide.

7. An automatic relief valve should be provided that can also be operated by the hand or finger. It should be placed on the exhalation bag.

8. The inhalation and exhalation bags should have a combined capacity of at least 8 liters. If a single breathing bag is used, it should have a capacity of at least 5 liters.

9. The breathing bags should be protected against accidental compression when the wearer is crawling through a low passageway.

10. The air within the circulating system should at all points be under a positive pressure of not to exceed 1 centimeter water gage, to insure that any leakage that may occur shall be outward and not inward.

11. All tubes and valves should be sufficiently large to permit the breathing of 100 liters of air per minute without undue resistance, with a positive pressure not to exceed 5 centimeters water gage, and no negative pressure even during the deepest and most rapid breathing.

12. Pressure gages should be regularly tested in comparison with a standard instrument. They should be calibrated in atmospheres and also in minutes of duration of the remaining oxygen supply, and should be placed where the wearer can easily see them, or provided with some device that will warn him when the supply is nearly exhausted.

13. Couplings and connections should be reduced to the smallest number possible and made strong enough so that even a heavy blow will not dislodge them, cause them to leak, or compress them so that air can not pass freely through them.

14. The production of heat in the absorber should be reduced to a minimum, and an efficient radiating or cooling device provided.

15. Parts of the apparatus worn on the back should be protected against damage when the wearer is traveling under a low roof. The valve regulating the oxygen supply, which in some forms of apparatus now projects to the side, should be protected against accidental closing.

16. In addition to training in a smoke chamber, as now practiced, men who are to take part in mine rescue operations should also be required, while wearing apparatus with full service equipment, to walk or run for 10 or 15 minutes at a pace of 5 miles an hour, and two hours or more at a varied pace, as herein described. These tests should be made a regular part of the drill and examination of men engaged or liable to be engaged in rescue work. The capacity of

each man to sustain the physical effort necessary should also be carefully determined in the manner herein described.

17. Experiments such as those herein described on the effects of carbon dioxide on the resting person, and on the effects of insufficient oxygen or excess nitrogen without considerable increase of carbon dioxide, may also be profitably demonstrated to men under training. It is important for their own safety that men who are to take part in rescue work should clearly understand the various forms of asphyxia and the premonitory symptoms of each. Such demonstrations should, however, be carefully supervised, as they are otherwise quite dangerous.

PUBLICATIONS OF MINE ACCIDENTS AND METHODS OF MINING.

A limited supply of the following publications of the Bureau of Mines has been printed, and is available for free distribution until the edition is exhausted. Requests for all publications can not be granted, and to insure equitable distribution applicants are requested to limit their selection to publications that may be of especial interest to them. Requests for publications should be addressed to the Director, Bureau of Mines.

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PUBLICATIONS AVAILABLE FOR FREE DISTRIBUTION.

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BULLETIN 20. The explosibility of coal dust, by G. S. Rice, with chapters by J. C. W. Frazer, Axel Larsen, Frank Haas, and Carl Scholz. 204 pp., 14 pls., 28 figs.

BULLETIN 45. Sand available for filling mine workings in the Northern Anthracite Coal Basin of Pennsylvania, by N. H. Darton. 1913. 33 pp., 8 pls., 5 figs.

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