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Apparatus and Techniques for Safe, Economical Work in Hostile Environments

H. Almqvist* and B. Jansson†

AGA Spiro, Lidingo, Sweden

Work that requires the aid of a breathing apparatus means an extra load for the wearer, as the apparatus is very often not properly designed from physiological and biotechnological viewpoints. In diving tasks economy becomes impaired by the fact that diving systems have not always been sufficiently adapted to different depths, types of work, and diving times. The systems presented here represent a great step towards the set goal, namely to make it equally safe and economic to perform tasks requiring a breathing apparatus as it would be to do the same work under normal conditions without apparatus.

Introduction

TO an increasing extent, work has to be carried out in nonbreathable environments such as poisonous gases, smoke, and underwater. There is therefore a growing need for breathing apparatus which will provide the wearer with pure breathing gas regardless of the nature of the atmosphere in which he is working.

To ensure complete safety, such apparatus must first and foremost prevent poisonous gas or water from entering the wearer's respiratory system. In order that apparatus shall not hinder the execution of work, it must be designed and constructed in such a way that the physiological and psychological capacity of the wearer can be used to the full.

The main requirement of a breathing apparatus is therefore that it should be able to provide breathing gas in the correct quantity and at the correct pressure for the task being performed at the lowest possible breathing resistance. In addition, the exchange of gas in the blood system should be equally effective as it is without breathing apparatus, which means that the dead space should be sufficiently small to prevent the rebreathing of CO_2 enriched exhaled gas. Furthermore, the apparatus should be light in weight and comfortable and must not interfere with muscular activity or blood circulation. Equipment that meets these requirements will allow a man to work safely in hazardous atmospheres with the same degree of comfort and efficiency as when working without breathing apparatus in normal environments.

The breathing apparatus which will be presented here are examples of equipment designed for improved efficiency. The goal when developing these sets has been to obtain the best economical solution. Underwater, one faces other problems such as temperature control, buoyancy, and visibility, but we are concerned here with the improvement of breathing apparatus itself.

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*General Manager.

†Marketing Manager.

There is a growing demand to be able to perform diving at greater depths, mainly because oil deposits are being discovered at increased depths. The heavy increase in the cost of diving equipment as well as the increased cost per hour of work at greater depths necessitates more efficient diving systems. Many are of the opinion that the diver should be replaced by something else—submarines, remote-controlled underwater vehicles, work sites at atmospheric pressure, etc. Of course, there is a depth limit below which divers can no longer be used. However, it might be possible to lower this limit considerably if the right resources are utilized in solving the problems connected with deep diving.

In order to make diving systems to meet the increasing demands for greater diving depths, a technical and physiological development program is necessary which requires great economical resources. We will discuss in the next section how these resources could be obtained.

Examples of New Breathing Systems

Compressed Air Breathing Apparatus for Poisonous Environments

As an example in this field, let us think of work in 100% chlorine gas which is a reality today in accidents involving chlorine gas vehicles, etc. The equipment needed in such cases is as follows.

1) A suit with protective helmet, gloves, etc., which gives protection from exterior damage through bumps, damages on the skin, variations in temperature, etc.

2) A communication system for reporting, etc.

3) Most important, an apparatus which guarantees pure breathing gas, no in-leakage from the surrounding atmosphere, full vision, and good comfort for the wearer.

Today it is possible to meet the above demands. The equipment shown in Fig. 1 costs less than $3,000 and it is possible to work continuously and comfortably with it for more than an hour. When extra air is supplied through a hose the duration becomes unlimited; the limiting factor is the man himself.

Conventional breathing apparatus work on the principle that air is supplied when one breathes in and produces a negative pressure in the mask and breathing valve. Since the pressure in the mask is negative during the inhalation phase, there is a risk that poisonous gas will be

Fig. 1 Breathing system for work in contaminated atmospheres.

drawn into the mask from the surrounding atmosphere possibly as a result of poor sealing between the mask and the face.

In the system described here, all risks of such leakage are eliminated since there is always an overpressure in the mask, during both the inhalation and exhalation phases. In the case of a poor seal between the mask and the wearer's face, there is a small outward leakage instead of an inward leakage and this is in direct proportion to the efficiency of the seal. The duration of the apparatus is not noticeably affected since the amount of air which is lost in this way represents only a minor percentage of the total air volume available in the cylinders.

By using cylinders with a charging pressure of 30 MPa (4200 psi) it becomes possible to use short and small diameter cylinders which make the apparatus neat and light with a long duration. The regulator unit and mask with breathing valve and the harness can be used with different types of cylinders, which means that the duration of the air supply can be chosen according to the work to be carried out. For work of long duration, the apparatus may be supplied with breathing gas through a hose from a separate gas storage system.

Dead space has been eliminated by an oro-nasal mask with separate inhalation and exhalation channels, which are completely separated from each other to prevent rebreathing of exhaled air. On inhalation (see Fig. 2) air from the inlet valve passes through channel B, over the inside surface of the visor and then through the non-return valves of the oro-nasal mask. On exhalation the air

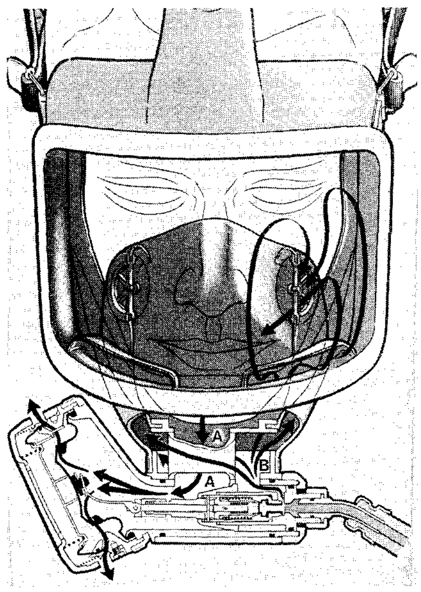

Fig. 2 Face mask with breathing valve.

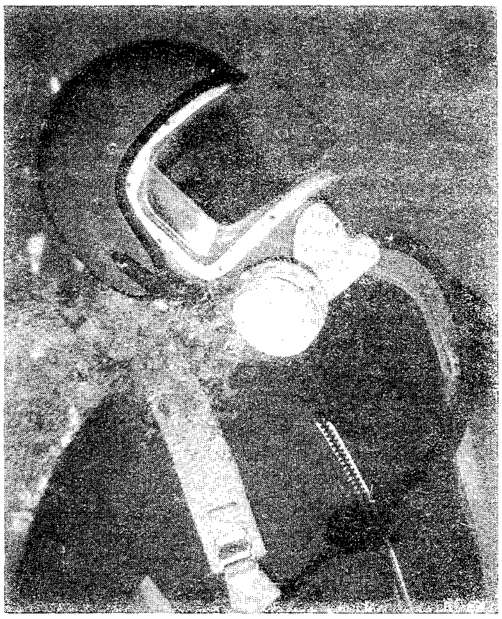

Fig. 3 All-purpose breathing apparatus.

passes through channel A and out through the exhalation valve. The separated channels give the extra advantage of keeping the glass free from moisture. The breathing valve is balanced which means a low breathing resistance and a high flow rate.

The preceding shows that it is possible to perform work efficiently and comfortably in a poisonous atmosphere at limited cost.

When transferring the worker from the just mentioned environment to water, known physiological problems arise because the partial pressures of the breathing gas increase in proportion to the depth.

Open Circuit Diving Apparatus

The traditional heavy diving equipment with hard hat and lead shoes has been used more than any other equipment for diving work all over the world. It is comfortable and simple but, of course, has certain drawbacks mainly because its design only permits work within a limited area since the diver cannot swim freely.

When compressed air breathing apparatus, the so-called SCUBA, was invented, this apparatus became an excellent complement to the heavy equipment. However, most models were equipped with a mouthpiece, which made them more suitable for sport diving or work in clean and warm water and when communication facilities were not necessary. Another disadvantage of the mouthpiece was that the air could not be moistened by inhalation through the nose. This lack of moisture, experienced as a feeling of dryness in the mouth, was formerly attributed to the dry air in the cylinders.

A diving apparatus should meet the same requirements previously specified for apparatus used in poisonous environments and, in addition, provide a higher rate of air flow. Therefore, the apparatus shown in Figs. 1 and 3 has been designed as an all-purpose set for use in any environment where breathing apparatus is required, such as in water, poisonous gas, low oxygen content, etc. This has, for example, made it possible for Merchant Navies to use the same apparatus for both firefighting and diving, resulting in economical advantages when purchasing, training, and servicing.

For reasons of comfort and economy and to avoid squeeze effects, a face mask is used instead of a helmet. To ensure comfort and to eliminate inhalation resistance, the breathing valve operates at a slight overpressure ever

Table 1 Gas mixture in relation to depth

Depth m	Depth ft	Diving gas
0–10	0–33	For practical and economical reasons, use air
10–24	33–79	Select the mixture on the curve p_{N_2} = 0.16 MPa (1.6 atm)
>24	>79	Select the mixture on the curve p_{O_2} = 0.18 MPa (1.8 atm)

for diving. This overpressure has the further advantage in that it prevents gas or water from leaking into the mask. For instance, there is no risk of inward leakage into a mask used with a constant-volume suit where air provides an insulation medium if used at helium-oxygen dives.

The balanced breathing valve with its high flow rate has made it possible to make regular dives on helium-oxygen mixtures to 150m (490 ft) and it has been tested in wet chambers down to 300m (980 ft) with excellent results.

Gas Heating System

Another important factor when diving is temperature control. Because of the low temperature of the water and its high heat conductivity, it is necessary to have a good insulation of the body and often additional heating. Sometimes it is also necessary to preheat the breathing gas, especially when a high percentage of helium is used.

For advanced helium-oxygen dives, one of the cylinders in the apparatus described may be exchanged for an electrical gas heater. The breathing gas hose and the electric cable enter at the bottom of the heater (see Fig. 4) and connect the heater to the quick coupling of the regulator. The gas cylinder is intended for self-rescue in case of hose supply failure.

Nitrox System

When ascending from depths of more than 10m (33 ft) one has to consider that inert gas is dissolved in the blood and tissues in proportion to diving depth and diving time. During ascent, the gas disappears but, if the ascent is made too quickly, gas bubbles of such a size are formed that they disturb the circulation. On longer dives to depths greater than 10m (33 ft) with air, it is therefore necessary to make a slow ascent, i.e., decompression stops.

An analysis of the different depths at which professional dives are made today will probably show different results for different countries. However, because harbours and similar constructions are common in all countries, it is likely that the majority of diving (approximately 80% in Scandinavia) is done in the depth zone of 10–25m (33–82 ft). An improvement of diving efficiency by means of direct ascent would therefore be of great economic importance. Furthermore, safety would be improved if a diver could always be taken up to the surface without decompression stops.

In practice, this improvement can be achieved by supplying the diver with an artificial mixture of air and oxygen instead of normal air. The exact proportions are determined in the following way.

As previously indicated, direct ascent can be made from 10m (33 ft) when diving on air. The nitrogen in the air has a partial pressure (p_{N_2}) at this depth, equal to 0.16 MPa (1.6 atm). The condition for avoiding decompression will thus be

$$p_{N_2} \le 0.16 \text{ MPa } (1.6 \text{ atm})$$

Fig. 5).

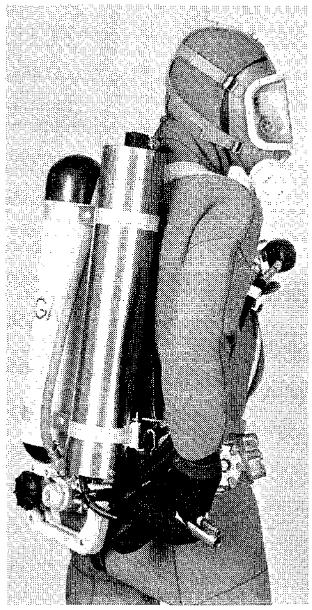

Fig. 4 All-purpose breathing apparatus with gas heater.

In order to oxygenate the blood, the breathing gas must contain at least the partial pressure of oxygen as air at the surface; i.e., the partial pressure of oxygen (p_{O_2}) must exceed 0.02 MPa (0.2 atm). Since too-high oxygen pressures will cause oxygen poisoning, the partial pressure must be kept below 0.18 MPa (1.8 atm) approximately. Thus the partial pressure of oxygen must be

$$0.02 \le p_{O_2} \le 0.18 \text{ MPa},$$

$$0.2 \le p_{O_2} \le 1.8 \text{ atm}$$

(see Fig. 5).

Maximum diving efficiency at relatively shallow depths is achieved if the breathing gas mixtures follow the dashed curve in Fig. 5. The information derived from the curve is shown in Table 1.

It is evident that decompression cannot be completely avoided at depths greater than 24m (79 ft) but the length of the stops can be considerably reduced compared to those for diving on air. For example, the decompression tables for 30m (98 ft) for air can be used for diving at 40m

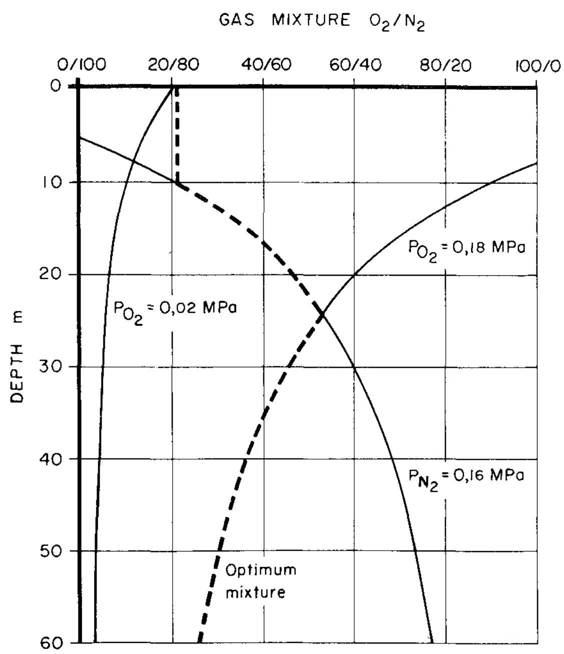

Fig. 5 Optimum mixtures in the Nitrox system.

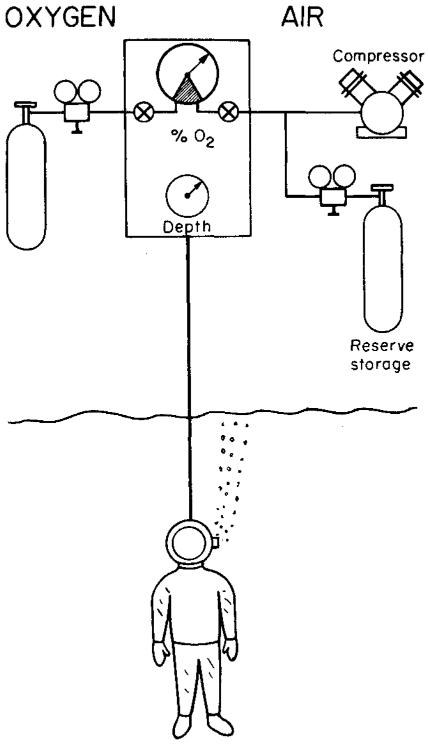

Fig. 6 Nitrox system.

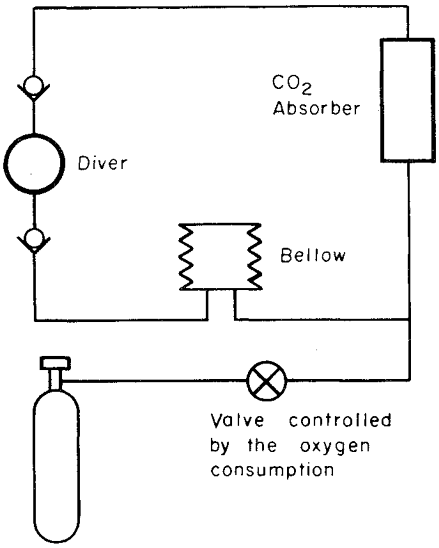

Fig. 7 ACOC system.

(132 ft) on an oxygen-nitrogen mixture. The following example illustrates the advantages of using the Nitrox system.

Suppose that a two-hour dive is to be made at 25m (82 ft) with one hour in the morning and one hour in the afternoon and a surface interval of two hours. When using air, the result (according to the US Navy decompression tables) will be a decompression time of 25 min for the first dive and 76 min for the second, i.e., a total inefficient time in the water of 101 min. When using Nitrox mixtures as per Fig. 5, direct ascent is allowed in both cases.

Figure 6 shows the principle of the Nitrox system. Air and oxygen are supplied to a gas-mixing unit which automatically mixes the gases in relation to the actual diving depth. Thus, as the depth is altered, the mixture is continuously adapted. The equipment is all mechanical. It contains a depth indicator and a gas concentration meter. By checking to see that the figures of these indicators correspond with the diagram as per Fig. 5, the attendant can make sure the diver gets the correct gas concentration at all times. If a fault occurs, a by-pass air system can be switched on and the dive may continue according to normal air diving tables.

ACOC System

In cases when the breathing gas cannot be supplied to the diver through a hose and the gas supply has to be carried in cylinders, the question of how effectively the breathing gas is utilized becomes of special interest. The systems which are in operation today are of three types: viz., open, semi-closed, and closed circuit.

For open-circuit systems, the duration T may be expressed as a function of the surrounding absolute pressure p and the workload W (considered equivalent to the air consumption) as per the formula T = Const./pW. Because duration decreases as depth increases, open systems are extremely uneconomical.

The semi-closed circuit systems existing today operate on the principle of a constant dosage of gas into a breathing circuit. Not including the loss of gas due to depth variations, the duration of such apparatus is independent of depth and workload, i.e., T = Const.

The disadvantage of this system is that the partial pressures of both oxygen and inert gas will vary considerably with different depths and workloads. It is therefore necessary to predetermine both duration and decompression time in a way which unfortunately gives an uneconomic utilization of the gas in order to avoid exceeding the physiological limits of the diver.

In closed-circuit systems, fresh oxygen is fed into the breathing circuit according to the demand of the diver. Not taking into account the gas consumption due to depth variations, the duration for this apparatus is T = Const./W.

Theoretically, closed-circuit apparatus gives the maximum possible duration. However, we have to distinguish between two different types of apparatus. In the first type, only pure oxygen is used. The apparatus can be made very simple and neat. Because of the risk of oxygen poisoning, this apparatus cannot be used for depths greater than approximately 8m (26 ft).

The other type of closed-circuit apparatus operates on mixtures of oxygen and inert gas. This type can be used at great depths and has a long duration. The disadvantage of existing apparatus of this type is that they are complicated and expensive. Furthermore, it is necessary to bring separate supplies of both oxygen and inert gas (or oxygen-inert gas mixtures).

In order to make a simple and efficient breathing apparatus with long duration at great depths, the so-called ACOC system has been developed. The principle is a mechanical system, as shown in Fig. 7.

The system consists of a breathing circuit containing a breathing bag and a CO_2 absorber. Normally the circuit is closed. An oxygen-inert gas mixture is fed into the circuit and oxygen is used by the diver. At certain intervals automatically controlled by the diver's oxygen consumption, the bag is emptied of gas; then fresh gas mixture is fed into the circuit. In detail, the exchange of gas is controlled in the following way. The accumulated volume of breathing gas which has passed the lungs is registered by a mechanical device on the breathing bag. When a predetermined volume has passed—which can be related to a certain oxygen consumption—a pneumatic system for exchanging of gases is activated. With the ACOC system, the available oxygen is effectively utilized. At the same time it is possible to control the partial pressure variations of both oxygen and inert gas within very close tolerances. This means that the mean pressure between the

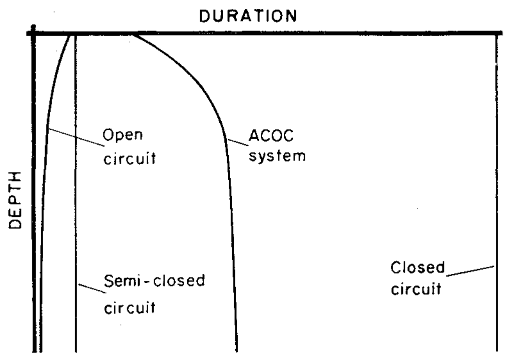

Fig. 8 Duration for different systems.

emptying intervals can be used to determine physiological data. The duration, which can be very long, may be expressed as

$$T = \frac{C_1}{W \cdot p}\left[\frac{(C_2 \cdot p + 1)(C_3 \cdot p - C_4)}{C_5 \cdot p - C_6} - 1\right]$$

where C_1, C_2, etc., are constants.

Figure 8 shows the general appearance of curves for duration as a function of depth at equal gas storages and workloads for different types of apparatus. The frequency of depth variations has not been considered. It should be noted that the durations for the semiclosed system and the ACOC system are very much dependent on the gas mixture used.

The accurate control of the partial pressures in the ACOC system allows the use of high mean oxygen partial pressure. This means low mean partial pressure of the inert gas or shorter decompression times.

Pressure Equalization and Buoyancy Control

For breathing apparatus with breathing bags, two functions are of great importance from physiological and efficiency viewpoints: 1) to keep the breathing resistance at an acceptable level and 2) to achieve constant buoyancy. In ordinary systems there is a considerable breathing resistance in certain swimming positions due to the static pressure difference between the breathing bag and the lungs.

In Fig. 9 a method of solving this problem is presented. The breathing bag has a rigid flap which moves when the diver breathes. This flap is loaded with a weight P which increases the pressure in the system when the bag is above the diver and decreases the pressure in the system when the bag is below the diver. In this way, the breathing resistance is eliminated. For example, the static pressure measured in the mouthpiece varied less than 1 in. WC (water column) when tested in the 2 positions shown in Fig. 9.

The design shown is used in an oxygen breathing apparatus with closed circuit. The oxygen dosage to the apparatus is controlled by the position of the flap. In this way the volume of the bag varies only with the breathing, which means that the diver has a constant buoyancy. It is an obvious fact, and has been verified in several tests, that a constant buoyancy greatly increases efficiency when swimming long distances.

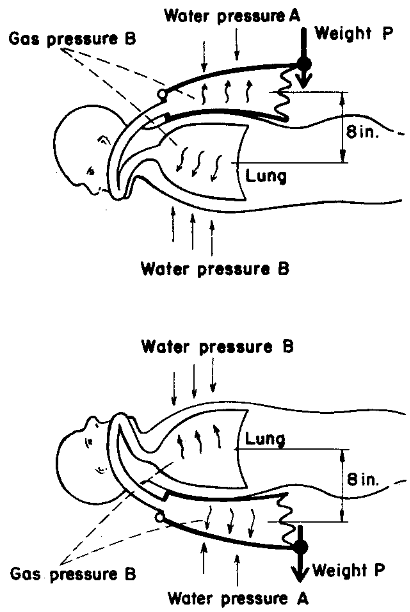

Fig. 9 Example of an effective breathing bag.

Conclusions

Among the examples previously described, the system for use in poisonous atmospheres allows work in a safe and economic way. The apparatus we have presented also represent steps towards a more effective and safe range of breathing equipment for diving.

However, much has to be done to give the diver the same safety and comfort, even at greath depths, as if he were working on land. To achieve this, both personnel and economic resources are needed. The question is, who is willing to provide these resources.

In any diving task, there are generally four different parties: 1) the customer who is to pay for the work, 2) the diving company who is the contractor, 3) the diver who does the job, and 4) the manufacturer of the diving system.

The diving company and the diver have a mutual interest in providing a safe and good service but hardly any interest in lowering the price more than to the level of their competitors. The supplier of the material is normally selling only parts of the system and has no interest in developing these parts more than to the level of the competitors. Finally, there is the customer who is, of course, interested in getting a cheap and good service. The problem today is that generally he cannot make any special demands as he does not see the possibilities of solutions.

A possible solution would be that the customer or the group of customers, by means of specifications and standardizations as well as by cooperation with experts, make general instructions as to how they want the future diving system to be. The specifications should be made so that the suppliers of material, who only have parts for complete systems, will be able to adjust their components to the possible system. If the customers also would indicate how much diving service they would buy during the years to come, then the right resources would be produced.