In contrast to the introduction of new naval equipment, a team of leading training agency officials and recreational instructors was convened some time ago for the first formal training program of a new oxy-nitrogen semi-closed rebreather. One would imagine that this group would comprise instructors who are focussed on diving safety and its evaluation but it is reported[6] that, in their spare time, some of them scuba dived solo on compressed air to 123 metres (400 feet). If this were so would *you* trust as safe a complex new breathing apparatus that is recommended by such an instructor? Validation demands appropriate laboratory evaluations by scientists and/or the military who are, and remain, independent.

Conclusion

More work needs to be done to confirm the safety of semi-closed breathing apparatus for recreational use. Gas samples for both O_2 and CO_2 from breathing bags at the O_2 extremes during shallow manned trials by exceptionally fit divers need to be taken at a laboratory experienced in diving physiology and analysed before settings such as flow rates are decided. A number of the claims made in the sport diving press and by the manufacturers about semi-closed rebreathers appear to be exaggerated, but the diving public is not sufficiently well informed to assess this. Diving doctors need to be aware of these problems and be prepared to educate if and when the agencies and manufacturers provide misleading statements.

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TESTING THE PERFORMANCE OF REBREATHERS

Mario Loncar and Hans Örnhagen

Key Words

Equipment, mixed gas, oxygen, performance, rebreathing.

Abstract

The growing interest in nitrox- and tech-diving among recreational divers has created the demand for rebreathers. Compared with open systems, this breathing apparatus offers long duration, silent diving and, in some cases, decompression benefits. Some rebreathers are on the market, but many are designed and built by the divers themselves, with a possible increase in the risks for accidents caused by malfunction of the unit.

When rebreathers are approved for use today, only the work of breathing and the scrubbing capacity, using a CO_2-injection technique, are tested. We suggest the use of a respiratory simulator capable of extracting oxygen. The respiratory simulator, using catalytic combustion of propylene, also imitates other aspects of respiration such as CO_2, humidity and heat production. With the respiratory simulator standardised tests can be performed which, together with a limited number of verifying dives with divers, should offer good possibilities of revealing weak spots in rebreather designs.

Introduction

The growing interest in nitrox and so called "technical diving", has created an increasing interest in rebreathers to meet various demands from recreational divers. Sports diving associations such as PADI and CMAS have already issued special procedures for mixed gas or enriched air diving for open circuit breathing equipment.[1,2] It is likely there will soon also be procedures for rebreathers because closed circuits are needed to allow full use of the advantages with nitrox in scuba.

The rebreather is not a new invention. It has been used in military diving for a long time and today is also used as a bail-out system in saturation diving. The use of rebreathers by sports divers means that a technically more advanced apparatus requiring more sophisticated dive procedures has spread to a population of divers, who use a less efficient surface backup organization than professional divers, with a vast variation in educational background. Furthermore, a lot of “home made” designs and constructions are likely to be built and used by divers with the necessary skills, who find the rebreathers on the market too expensive.

In this situation we would like to present a test procedure that can be used for testing and approval of all kinds of closed and semi-closed breathing equipment.

Rebreathers

Rebreathers can be grouped into three main categories, closed, semi-closed and pure oxygen rebreathers. The distinction between the different types of rebreathers is based on the method of controlling the gas composition in the breathing circuit. Looking at complexity level of rebreathers, the oxygen rebreather is usually the least complex apparatus, based on either volume demand or constant mass flow with bypass. The semi-closed breathing apparatus can be simple and have a constant mass flow adjusted to the oxygen content of the supply gas, or be based on more sophisticated principles, e.g. supply gas additions in relation to the need of the metabolism as measured mechanically through the ventilation. Finally the highest sophistication can be found in the closed rebreather in which pressure and oxygen sensors, together with electronic control systems and valves, provide a constant PO_2 in the breathing gas. This complex scuba requires a higher degree of training and more maintenance than the other types.

The semi-closed rebreather with a pre-set gas mixture and fixed flow of supply gas will probably be the most frequently used rebreather for recreational diving, because of the less complex design and lower price compared with electronically controlled closed circuit rebreathers.

Compared with open systems, closed and semi-closed breathing systems offer long action duration, gas savings, and in some cases decompression benefits. In addition stable buoyancy and silent diving, which originally made the rebreather useful in military diving, is appreciated by underwater photographers and zoologists. These advantages are accomplished at the cost of the equipment being more complicated, more expensive and requiring a higher degree of user training. The complexity of rebreathers introduces risks that are not found in open circuit breathing equipment. In table 1 some of the major risk factors are listed.

TABLE 1.

MAJOR RISK FACTORS USING REBREATHERS

Problem	Possible cause
Hypoxia	
	Gas supply not opened or empty
	Wrong supply gas or setting of supply flow
	Failure of sensors, control circuit or valves
	Inappropriate purge procedures
Hyperoxia	
	Wrong supply gas or too deep dive
	Failure of sensors, control circuit or valves
Hypercapnia	
	Scrubber not filled or material worn out
	Inappropriate scrubber performance at low temp
	Scrubber flooded
Excessive work of breathing	
	Wrong type of scrubber material (granule size)
	Lack of maintenance
	Scrubber flooded
Caustic cocktail	
	Inefficient water trap (design or maintenance)
	Inappropriate use of mouth piece shut-off valve
Water entry	
	Leaks because of lack of maintenance or error in the assembly (e.g. missing gaskets)
Loss of breathing gas	
	Rupture of hose or bag. Technical failure

Although most rebreather designs have built in countermeasures to handle the problems listed, this is not the case with all, and one fears that the design of budget versions for recreational diving will lack these countermeasures. A test procedure should therefore be able to reveal the weak spots and help to improve both the design and the user’s manual, to make the use of the rebreather safe and easy. This is most important when completely novel designs, “home made” equipment, or equipment from less well known manufacturers are to be tested and evaluated.

The importance of an adequate minimum oxygen partial pressure (> 20 kPa) to avoid hypoxic loss of consciousness, and a maximum PO_2, (usually < 160 kPa) to avoid oxygen convulsions is easily understood. Examples of accepted maximum PO_2-levels are shown in table 2 in which limits from different authorities are listed.[1-5] In military operations higher risks can be accepted and thus often a higher PO_2 is allowed, see fig 1.[3,6]

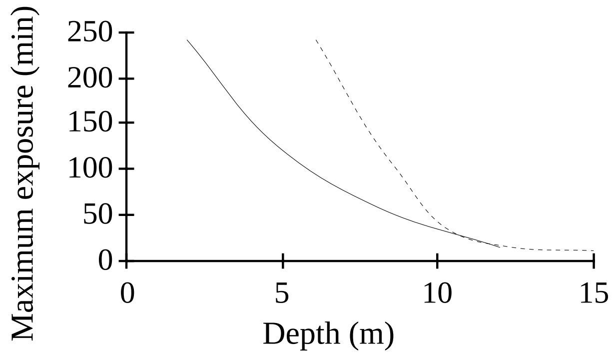


Figure 1. Maximum permitted oxygen partial pressure and maximum exposure time during oxygen diving in the Swedish Navy (solid line) and the US Navy (dotted line),

TABLE 2

MAXIMUM ALLOWABLE PO_2 IN MIXED GAS DIVING

Regulations	PO_2 [kPa]
Swedish Navy, nitrox	190
US Navy, bounce dive heliox	180
CMAS, mixed gas diving	160
UK commercial diving regulations	160
Norwegian commercial diving regulations	160
PADI, mixed gas diving	140
Swedish commercial diving regulations	140

TABLE 3.

THE CONSEQUENCES OF THREE DIFFERENT OXYGEN FRACTIONS IN THE INHALED BREATHING MIX DURING A 20 m DIVE USING NORDIC SPORTSDIVING TABLES (1995).[10]

FO_2	EAD	No stop time /N_2 load	N_2 load after 40 min dive	Surface interval to reach B
35%	14.7 m	85 / J	F	5:01
30%	16.6 m	60 / I	G	5:31
25%	18.5 m	40 / H	H	6:01

The frequent use of high oxygen partial pressures can also affect other organs and reversible changes can be detected in lungs and blood even if no diver performance decrement is observed.[7] It is thus highly recommended to follow and limit the accumulated daily “dose” of oxygen if high oxygen partial pressures are used .[8,9]

Less well understood is the importance of knowledge about PO_2 through the whole dive and thereby knowing the inert gas partial pressure. This allows a safe and optimal calculation of the nitrogen loading during the dive, and the need for surface intervals between dives and/or decompression profiles. An example is shown in table 3.

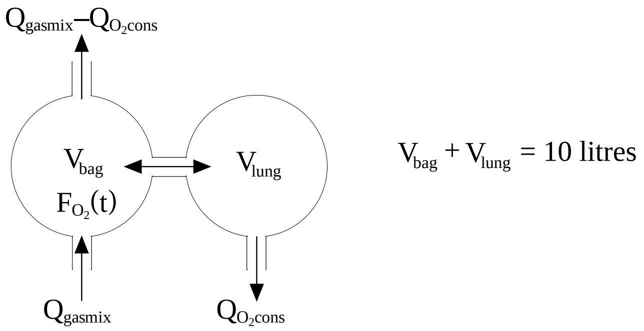
Increase in the inspiratory PCO_2 can cause not only increased ventilation, dyspnoea and discomfort, but also jeopardise survival through effects on consciousness. For a summary of CO_2 effects on man during diving see.[11]

Test procedures

When evaluating open circuit demand breathing equipment, the work of breathing (WOB) and peak pressures have traditionally been the most important parameters.[4,12] The standard technique for testing the performance of open breathing equipment is with the use of a breathing simulator. This method is also appropriate for testing the WOB in closed and semi-closed breathing systems. Tidal volume is usually measured as the displacement of the breathing simulator piston. The pressure is measured as a differential pressure between the inside of the mouthpiece and a suitable reference point.[13] It is important that all measurements are made in water to include hydrostatic and hydrodynamic loads.

In open circuit demand breathing systems the inhaled gas fraction and consequently the gas partial pressures are well defined and directly depending on the dive depth. This is not the case in closed and semi-closed breathing apparatus. When evaluating a rebreather, besides the WOB, the performance of the carbon dioxide scrubbing system, the inhaled gas fractions and partial pressures have to be evaluated. The gas concentrations and partial pressures vary depending on the technique for adding gas to the rebreather, the oxygen uptake of the user and the ambient pressure.

Because of the consumption of oxygen from the circuit, the inhaled oxygen fraction is not same as in the supply gas. Theoretical models describing the behaviour of rebreathers are available and today the oxygen supply system is usually evaluated theoretically by calculations. In addition human test dives are made in experimental chambers where sampling lines for gas analysis can be



$$F_{O_2}(t) = \frac{Q_{gasmix} \cdot F_{O_2 gasmix} - Q_{O_2 cons}}{Q_{gasmix} - Q_{O_2 cons}} + \left(F_{O_2 start} - \frac{Q_{gasmix} \cdot F_{O_2 gasmix} - Q_{O_2 cons}}{Q_{gasmix} - Q_{O_2 cons}} \right) \cdot e^{-\frac{Q_{gasmix} - Q_{O_2 cons}}{V} \cdot t}$$

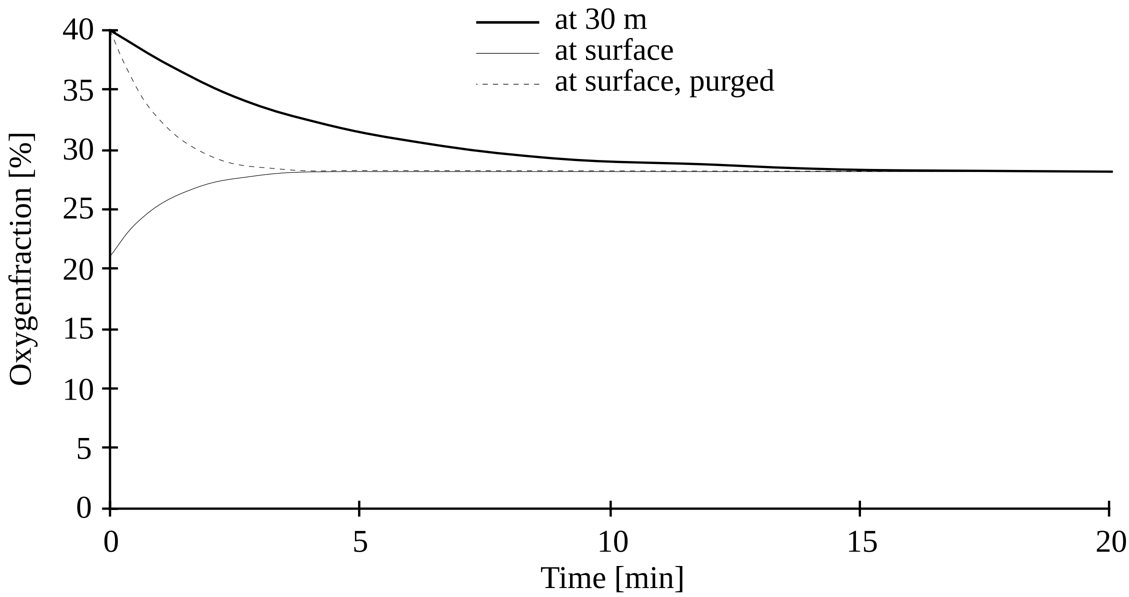


Figure 2. An example of a calculation of the oxygen fraction in a semi-closed rebreather at 0 m (dotted line) and 30 m (thick solid line) with a fixed gas mixture containing 40% O_2 added at a rate of 12 l/min (STPD) and an oxygen consumption rate of 2 l/min (STPD). The oxygen fraction when the rebreather-lung system is not purged at the start is illustrated by the thin solid line.

attached. In a design using a constant mass flow of a fixed gas mixture, it is possible to solve the equations explicitly. The equation and graph in figure 2 is an example of how to calculate the oxygen fraction in a rebreather with a constant mass flow of a fixed gas mixture:

When using semi-closed rebreathers with pre-set gas mixtures, incorrect use of gas mixtures and wrong settings of gas supply flow can impose hazards such as hypoxia and hyperoxia as illustrated in fig 3. Using air as supply gas in a constant mass flow rebreather, when no proper mixture is available, will undoubtedly lead to hypoxia if the supply flow is not set unreasonably high. Because of this risk it is important that the gas bottle connection in the rebreather is such that air bottles can not be connected to a rebreather designed for mixes of higher oxygen content.

Carbon dioxide can be added to test scrubber performance in a simulator test but no simple method for extraction of oxygen is used routinely today. Therefore divers are needed to verify the actual performance of the apparatus. Humans vary both intra- and inter-individually, which makes objective comparisons very difficult, and a large number of dives have to be performed to allow statistical analysis.

The use of divers when testing the equipment in extreme situations such as at great depth, low temperatures and long exposure times also imposes ethical limitations. We therefore suggest the use of a simulator, that can extract oxygen, deliver CO_2, heat, and water vapour for these tests.

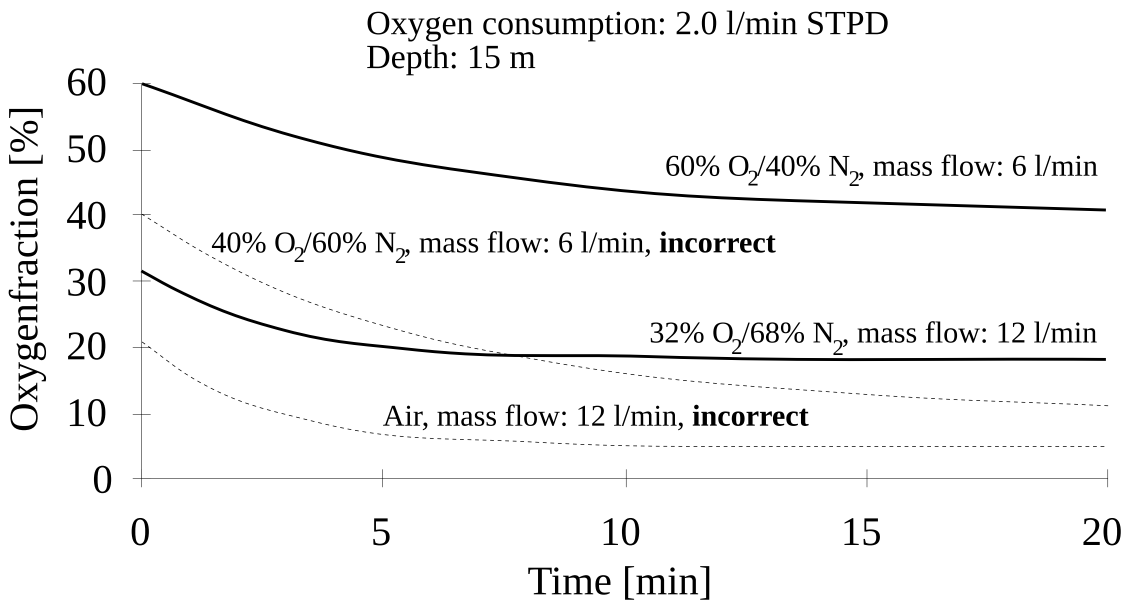


Figure 3. An example of the oxygen fraction in a semi-closed rebreather at 15 m and an oxygen consumption rate of 2 l/min with four fixed gas mixtures. The mixtures are added at two different rates, 6 l/min (STPD) and 12 l/min (STPD). The two mixtures 60% O_2 at 6 l/min (solid line) and 32 % O_2 at 12 l/min (solid line) do not produce hypoxia. The other two, 40% O_2 at 6 l/min (dotted line) and air at 12 l/min (dotted line) will produce hypoxia and are labelled incorrect.

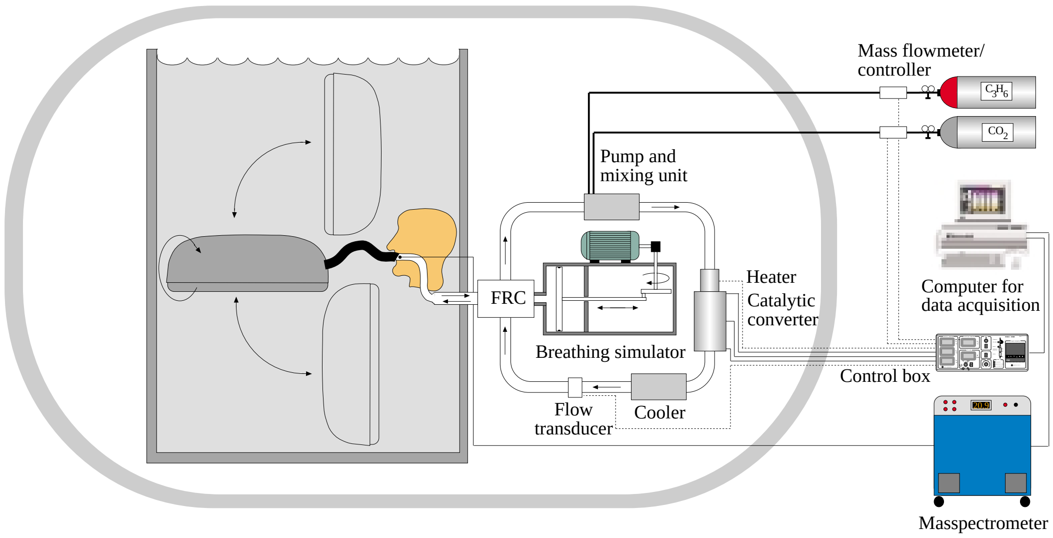


Figure 4. A schematic figure of the respiratory simulator. To the left is shown how the apparatus is tested in four different attitudes.

Improved test procedure with respiratory simulator

To overcome the shortcomings of the present testing methods for rebreathers a respiratory simulator (FOA respiratory simulator) incorporating both the ventilatory and the metabolic components of the human respiration has been developed.[14] The respiratory simulator uses catalytic combustion of propylene gas resulting in an oxygen consumption directly proportional to the flow of fuel added. The V_{CO_2}/V_{O_2} (respiratory quotient) with the gas used is 0.67, which makes addition of extra CO_2 necessary. This makes it possible and easy to vary the "respiratory quotient" from 0.67 to over 1, which can be an advantage in some situations. The internal volume of the unit is small, ≈ 1.5 litres, and this makes it possible to have a volume of the whole system comparable to the functional residual capacity of humans of different size. This is important when the exact gas composition is measured during changes in ambient pressure and when simulating breath-holding or other changes in the breathing pattern.

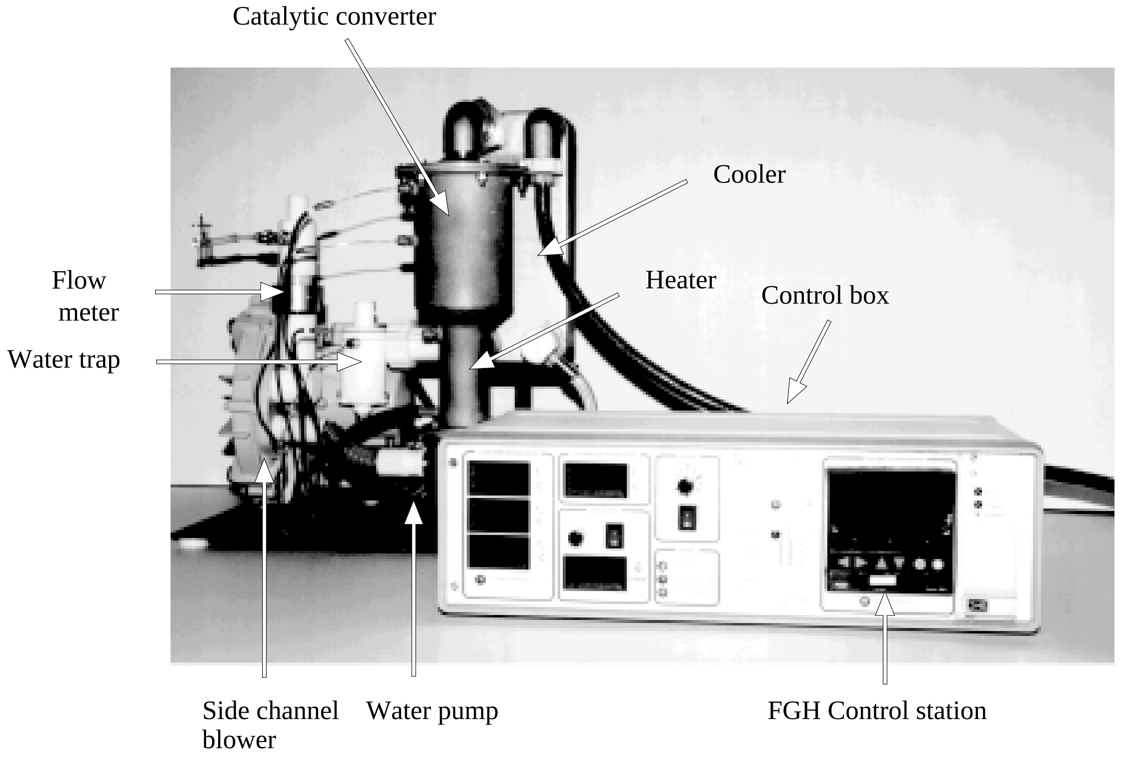


Figure 5. A photo of the metabolic simulator. For size reference, the control module is 48 cm (19") wide.

Advantages using the respiratory simulator:

- Objective and reproducible measurements of gas concentrations and time constants in closed and semi closed breathing apparatus under different diving conditions.
- Ability to test the equipment under extreme test conditions without exposing divers to risks.
- Man and time saving procedures because no diving is involved.

Figure 6 shows screen dumps from the data acquisition system, showing the high degree of similarity of inspiratory/expiratory gas contents between the simulator (to the left) and human (to the right). Since the "metabolic process" continues also when the breathing machine is stopped, it is possible to simulate breath holding with the respiratory simulator (not shown in the graph).

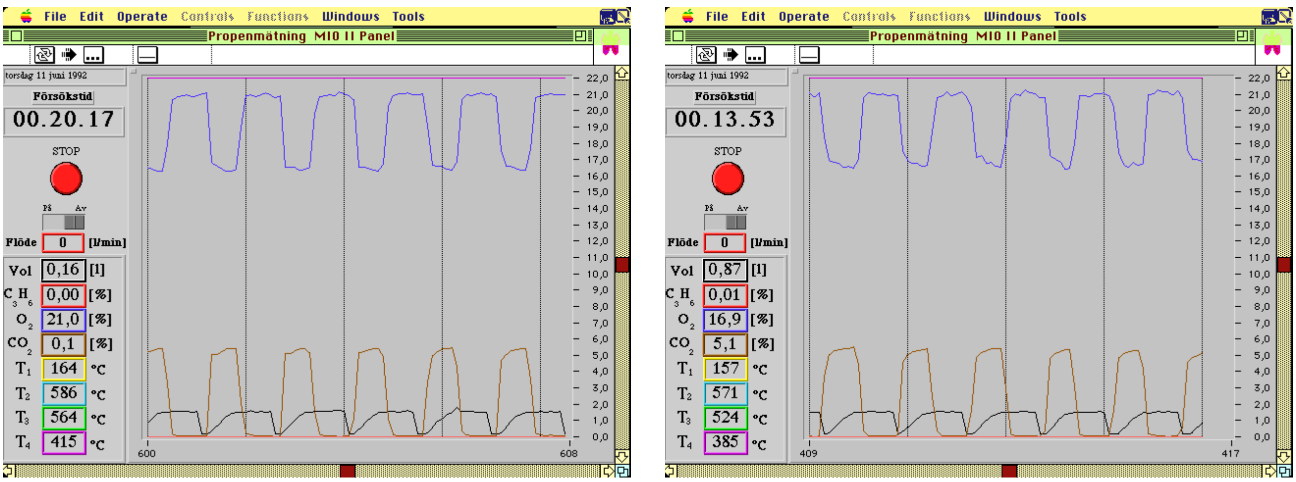


Figure 6. Recordings of O_2 and CO_2 during respiratory cycles of the respiratory simulator (left) and a human (right).

Suggested test protocol

We suggest that a testing procedure for rebreathers, should include:

- Work of breathing (WOB), peak pressures and static loading test in at least four different attitudes (head up, head down, prone and supine).

- CO_2 scrubbing capacity test (time until P_iCO_2 0.5, 1.0 and 1.5 kPa)

- Tests of O_2- and CO_2-fractions and partial pressures and also their rate of change during simulated dives to, and ascent from, the maximum approval pressure during at least two different oxygen extraction rates (rest and 3.0 l/ min [STPD])

With the respiratory simulator all of the above mentioned tests can be performed in the same dive thus saving time, effort and money. A limited number of verifying dives with human subjects should also be performed after the unmanned testing.

In figure 7 is illustrated how the suggested test procedure was used in a quality assurance process to verify the function of an improved version of the Interspiro semi-closed breathing apparatus for mine clearance.[15] In the graph are some of the measured parameters illustrated during a wet 57 m dive using the FOA respiratory simulator in the wet pot of the chamber system at the Swedish Navy Diving Centre. The oxygen fraction is the average inhaled fraction from one rebreather. From the graph it is seen how the oxygen fraction is slightly reduced at the highest work load near the surface, but stays well above the minimum 20%. During the rapid compression the breathing bag and lung volumes are filled with supply gas and the highest oxygen partial pressure is recorded when the bottom is reached. A 44 min decompression should follow the 25 min bottom phase if a human performed the test dive. With the simulator, ascent to surface can be done directly, thereby saving time. The real advantage is in the fact that once the equipment is installed, one person can manage several tests during a day, which is impossible if divers are involved.

Conclusion

To allow extensive tests of rebreathers at reasonable cost and manpower, a respiratory simulator capable of consuming oxygen has been developed. It is our recommendation that in the future rebreather approval should include tests of the oxygen delivery system to assure oxygen partial pressures are within acceptable limits in addition to other important parameters.

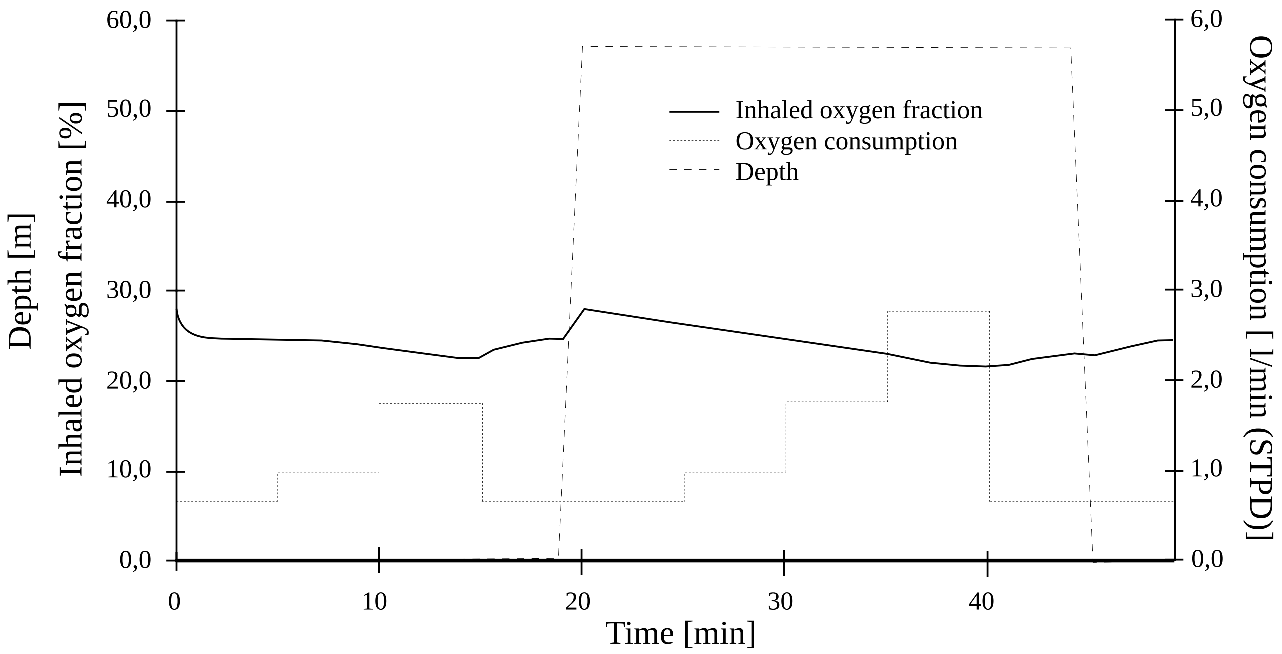


Figure 7. An example of a test of an Interspiro DCSC rebreather using the described respiratory simulator. The inhaled oxygen fraction (solid line) as a function of oxygen extraction (dotted line) and pressure (broken line) is shown over the 50 min test period. The minute ventilation at different oxygen extractions follow the Norwegian Petroleum Directorate (NPD) rules for corresponding CO_2 productions (NPD 1991).

Acknowledgment

This work was supported by:
National Board for Industrial and Technical Development
Swedish Defence Material Administration
Norwegian Underwater Technology Centre.

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REBREATHER PHYSIOLOGY

RW (Bill) Hamilton

Key Words

Equipment, mixed gas, oxygen, physiology, rebreathing.

A diver breathing on open-circuit apparatus "throws away" a great deal of perfectly good gas and this "waste" increases with increasing depth. A rebreather recovers and reuses much of this inert gas that would otherwise be lost; it removes the CO_2 and replaces the oxygen consumed.

The basic characteristics of rebreathers in general, a bit about their history and the problems of semi-closed rebreathers have been discussed by Dr Elliott.[1,2]

Rebreather essentials

Only a small amount of the air a person inhales on each breath is actually used by the body. Virtually all of the nitrogen and most of the oxygen is exhaled with a little CO_2. A rebreather enables most of this exhaled breath to be reused and must have a few essential components. These are a breathing loop with valves to control the flow direction, a counterlung or breathing bag, a canister to absorb CO_2 and some way to add gas when the volume in the breathing bag decreases. Valves maintain the flow in a constant direction and breathing pushes the gas through the canister.

For diving a rebreather must have a compliant volume, a space that can expand by the same volume that the diver exhales and inhales on a breath. As a result the total gas volume does not change appreciably, so buoyancy does not change during breathing. Usually it is the diver's