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REBREATHERS : AN INTRODUCTION

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Introduction

Recreational divers with money to spend turn to the latest technology. Current magazines for divers have numerous articles on rebreathers for deep cave and wreck exploration. Other rebreathers for use with oxy-nitrogen at shallower depths are available for the less adventurous diver. Although some may incorporate electronic sensors and controls, the basic principles of today's rebreather are the same as when they were first used, more than 100 years ago.

In 1880 a railway tunnel being constructed under the river Severn became flooded and attempts to shut an open sluice were unsuccessful. Standard divers were unable to get there because it was too difficult to drag 1,200 feet (364 m) of air hose that far. Mr Henry Fleuss of Siebe Gorman volunteered to try and reach it. Two years previously Henry Fleuss had designed and made the first self-contained rebreather.[1] His equipment included a copper cylinder, which was charged to 30 atmospheres with oxygen, and a scrubber which contained string soaked in caustic soda. Oxygen was let into the breathing bag "when needed". After several attempts to reach the open sluice, each of an hour or more duration, with the foreman of the labourers as his attendant, he decided to send the diver Alexander Lambert, because he was more familiar with the workings in the tunnel. On his second attempt Lambert managed to move some railway lines out of the way and completed the task of closing the sluice. His total dive on oxygen was 90 minutes at a depth of 40 feet (12 m; PO_2 2.2 bar). That railway tunnel between Bristol and Cardiff is still in use today.

A glance through the pages of Deep Diving and Submarine Operations [1] reveals that in the next 30 years or so there was a variety of designs for closed circuit rebreathers, including the use of sodium peroxide to both absorb CO_2 and generate oxygen, a principle still used in some coal mine escape apparatus. In 1912 a self-contained suit with a rigid helmet was devised for use with 50/50 oxy-nitrogen at 5 litres (surface equivalent) flow through an injector that also, on the venturi principle, sucked the helmet gas through the CO_2 absorber.

Subsequently it was the military in World War II[2] who developed closed circuit oxygen rebreather techniques for covert operations and also, at depths down to 55 m (180 ft), used oxy-nitrogen semi-closed circuit apparatus for acoustic mine clearance because of its low bubble noise.

In the early 1970's, to conserve expensive helium, a semi-closed rebreather was developed to use pre-mixes of helium, containing oxygen at less than 20%, for use out of a diving bell at depths below 50 m. Its operational use was limited by the need to ensure oxygen levels within the breathing bag that were neither hypoxic nor hyperoxic both at rest and when hard at work. To achieve this the flow rates of pre-mix had to be increased to a level that the set was no longer competitive vis-a-vis open circuit apparatus.

Meanwhile, largely inspired by the US Navy's SEALAB program, oxygen sensors had been introduced, enabling the rebreather to be developed as a closed circuit rig at depths at, and deeper than, the limit of semi-closed technology.

An introduction to rebreathers needs first to clarify the different categories of rebreathers (Fig. 1) and to consider their merits and disadvantages of their different gas flow systems. These and other important aspects of breathing apparatus performance and design are discussed in greater detail elsewhere.[3]

Closed circuit oxygen

This type of apparatus has a carbon dioxide scrubber and a simple counterlung or breathing bag which is full of oxygen from which the diver breathes. As the oxygen is consumed so more oxygen needs to be released into the breathing bag from the cylinder carried by the diver.

In Henry Fleuss' apparatus the oxygen was supplied "on demand" and replenished when the diver thought that the rebreathing bag was getting low. This is a dangerous procedure because, during the dive, dissolved nitrogen is being washed out of the body into the rebreather's closed system. As the bag diminishes in volume with the consumption of its oxygen, nitrogen comprises an increasing percentage of the bag's content. Unless more oxygen is released into it in good time, the point could be reached when the counterlung provides the diver with a hypoxic mix. Hypoxia is usually associated with a CO_2 build up but, with a CO_2 scrubber in the circuit, the diver could be quite unaware of the changes of inspiratory gas composition. The diver may pass gently into unconsciousness due to "dilution hypoxia" and death is likely to follow. This may happen at depth but can be precipitated by the fall of PO_2 occurring during ascent.

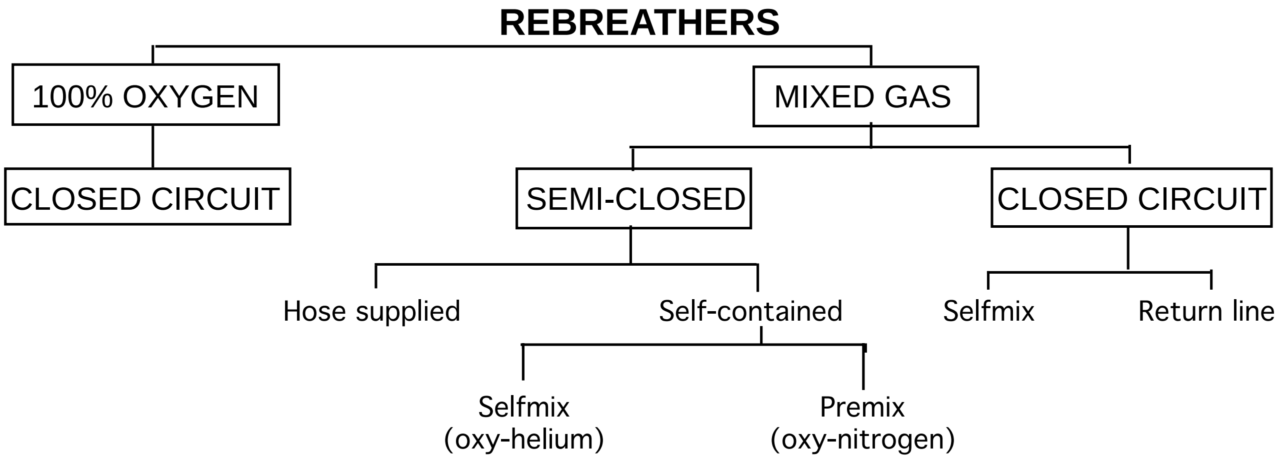

Figure 1. A classification of rebreathers.

To avoid this, an oxygen diver breathes for 2 minutes from the breathing bag while at the surface and then empties it and its contained nitrogen before recharging the counterlung with pure oxygen. Then the descent can begin. This one "nitrogen wash out" is sufficient for a 90-minute dive using a typical naval closed circuit rebreather.

Because breathing "on demand" can be particularly hazardous it is generally reserved for combat situations in which a lack of bubbles from the diver is essential. At all other times the diver is provided with a constant flow of oxygen into his breathing bag at a basic rate, usually a constant surface equivalent volume (constant mass) of 1.5 litres per minute ($l.min^{-1}$). This is achieved by an acoustic reducer, a tube within a brass plug which has the orifice engineered to allow only a relatively small mass flow of oxygen molecules through it. This flow rate reaches the speed of sound which means that, given a constant pressure of supply to the reducer, the flow remains constant regardless of the environmental pressure of the diver.

In spite of this constant mass flow, dilution hypoxia can still be a hazard. If, for instance, the oxygen bottles have perhaps leaked and they empty earlier than expected, the diver may be unaware that his counterlung contains an diminishing percentage of oxygen as he heads towards an anoxic death. Another problem can occur if the working or swimming diver exceeds 1.5 $l.min^{-1}$ without noticing that the bag is getting smaller. The diver is "beating the flow" and could be heading for hypoxia, especially if he fails to flush the counterlung with fresh oxygen before beginning the ascent with its associated drop in oxygen partial pressure.

As Alexander Lambert showed, this type of self-contained apparatus works, but the early oxygen divers were probably not fully aware of the many hazards to which they were exposed. As the particular hazards of hypoxia, hyperoxia, hypercarbia and "soda lime cocktail" became more recognised, rebreather designs and diving procedures were developed to reduce these risks. The hazards of oxygen neurotoxicity were recognised by naval authorities and so, notwithstanding the use of oxygen by some combat swimmers for short periods at greater depths, the use of oxygen sets was limited to 25 ft (7.6 m; PO_2 1.8 bar) when swimming with fins.

Semi-closed mixed gas

Of the many varieties of semi-closed rebreathers that have been made available to the diver, the designs most close to those now being introduced to recreational diving are those using an oxygen-rich nitrox pre-mix. These were developed from the closed circuit oxygen sets by the navies who needed them for defusing acoustic mines. The other types of semi-closed rebreather need to be mentioned briefly for clarification and completeness.

HOSE-SUPPLIED

The first semi-closed rebreather with a hose was a modification of the deep standard divers' open-circuit oxy-helium helmet. Within the large semi-rigid system of the helmet and associated dry suit there was no need to have a counterlung in the circuit. A certain amount of rebreathing occurred within the regular helmet which was supplied from the surface at a predetermined flow rate, sufficient to minimise the carbon dioxide build-up. In the deeper versions of the oxy-helium helmet, the constant flow of fresh gas to the diver was fed through a venturi which caused a proportion of the gas in the helmet to be recirculated through a soda-lime canister. This apparatus was used until the early 1970s.

Quite different is the commercial breathing apparatus which uses a hose to provide oxy-helium to a semi-closed set with a counterlung. This, in its basic design principles, is very similar to the shallower oxy-nitrogen sets which require less gas and so do not require a hose. This oxy-helium semi-closed set necessarily uses oxygen percentages of less than 21% and so is used not from the surface but from a diving bell. To allow for the varying levels of oxygen consumption within a specific depth range, the flow rates have to be relatively high. This means that, at around 150 to 200 m, these semi-closed sets no longer provided cost savings over open-circuit oxy-helium demand breathing apparatus. Nevertheless there are several locations where these units are still operational.

SELF-CONTAINED SELF-MIX (OXY-HELIUM)

There is a semi-closed set which was developed for the Royal Swedish Navy and which is a “self-mix” unit. It has a constant oxygen flow rate and a separate helium supply which is increased with depth. With such a breathing apparatus the potential problems again relate to the varying need for oxygen during a dive. There is also a Canadian semi-closed breathing apparatus which is said to deliver a constant partial pressure of oxygen to a depth of 95 m but no technical reports have been reviewed and, as with any new apparatus, one would want to see rigorous manned testing at high work levels with oxygen monitoring before accepting it.

SELF-CONTAINED PREMIX (OXY-NITROGEN)

At shallow depths, in contrast to the hose-supplied and self-contained oxy-helium semi-closed rebreathers which need to have less than 21% oxygen at depth, the oxy-nitrogen semi-closed rebreathers use a pre-mixed gas of oxygen enriched air. The basic principles are very similar to those of the oxygen apparatus already described and, with a CO_2 scrubber in the system, require a constant flow into the breathing bag of a gas with a known O_2% and at a pre-determined rate.

The flow rate needs to be pre-set and there are two ways in which this can be done. The simplest is to set a sonic reducer, similar to that used for 100% oxygen flow, but at a higher set flow according to the mixture used. This can be illustrated by naval clearance divers breathing apparatus (CDBA) when used to its maximum operational depth of 180 feet (55 m) using 32.5% oxygen mix. The *constant mass flow* rate is set at 13 $l.min^{-1}$ and, for oxygen consumptions ranging from 0.25 to 2.5 litres per minute, this provides an oxygen PO_2 in the counterlung between 0.21 and 2.0 bar. This high partial pressure of oxygen will occur when the diver is at rest and was accepted at that time for operational use. It has since been reduced by defining a shallower maximum depth of use. In some circumstances, there can also be a risk from hypoxia due to an oxygen percentage which has provided an adequate partial pressure while at maximum depth, but which may be insufficient to maintain consciousness as the diver reduces his ambient pressure during ascent. So, for additional safety as when using closed circuit apparatus, the diver empties the counterlung and refills it before commencing the ascent. Although this procedure may raise the inspired PO_2 slightly above 2.0 bar, this is only transient and was, on balance, considered safer than the risk of hypoxia during ascent.

Equally ingenious, but slightly more complex to use, is the *constant ratio* semi-closed circuit principle.[4] This device was first used by the French Navy and is based on designing the breathing bag as a bellows system. Within the counterlung is a separate smaller (1:11) concertina bellows, the slave, which follows the movements of the main breathing bag precisely. Thus each of the bellows are filled at the same time when the diver exhales but, when he inhales from the main compartment, the contents of the slave (one eleventh of the previous exhalation) are discharged into the sea. The larger of the bellows is fed on demand from the pre-mix gas supply. Unlike the constant mass flow supplied semi-closed sets, the constant ratio set has a diminished endurance because of increased gas usage at increased depths. The calculation of inspired oxygen percentage is slightly more complex requiring also knowledge of the diver’s ventilation coefficient: the relationship between oxygen consumption and minute volume, a relationship that could be different in those divers who are “CO_2 retainers”. The mathematical and physiological principles are outlined elsewhere.[4] There seems to be no recreational application of this principle, yet.

The majority of the nitrox semi-closed breathing apparatus now being marketed to the recreational diver is based on a pre-mixed gas delivered by constant mass flow. They use the same principles already described for military use but avoid the CO_2 problems arising from the large dead space of pendulum breathing by having an inhalation and an exhalation hose, with the CO_2 scrubber in the loop circuit. Nevertheless, the selection of a percentage of oxygen for a particular depth range and of a constant mass flow rate for it inevitably leads to a compromise between the conflicting physiological needs of avoiding hyperoxia and hypoxia at different work rates. The biggest unknown, and a cause for concern if hypoxia is to be avoided, is the range of oxygen consumption to be encountered during the dive, particularly if, for a minute or two, it is necessary for the diver to expend maximum physical effort.

Thus, diving with semi-closed rebreathers introduces several hazards which are not encountered by those diving on open-circuit compressed air scuba. The potential consequences include dilution hypoxia, hyperoxia, hypercarbia and “soda-lime cocktail”. The degree of risk to the diver from these hazards will be modified by the design, flow rates and other parameters of the particular set used and by the procedures which the diver should be taught. These procedures are due to be considered in a later paper.

Closed-circuit mixed-gas

The self-contained and the hose-supplied closed-circuit mixed-gas apparatus are both closed circuit but are totally different designs. They share only the concept of recirculating the exhaled gas as a pragmatic response to the high cost of the helium which would be wasted if the diver were using an open-circuit demand breathing apparatus.

RETURN LINE CLOSED-CIRCUIT

Dating from the 1960s, the concept of a bell-mounted closed-circuit system for hose divers has proved attractive. The gas is supplied by hose from the bell to the diver on demand and after exhalation is returned through a necessary exhaust regulator and valve by a parallel hose to the bell where the CO_2 is scrubbed and the O_2 replenished. These "push-pull" systems lost their commercial battle to similar systems mounted not on the bell but at the surface. In the deck-mounted systems, a return line takes the exhaust gases from the diver via the bell to the system on board the diving support vessel where it is purified and returned to high pressure tanks for re-use. One reason for lengthening the circuit to the surface was a need for easy access by the deck crew to the system for maintenance. An advantage of these extended closed-circuit systems is that the diver breathes from a conventional demand valve during the dive and, provided the technology does not fail, should not be at risk from hypoxia, hyperoxia or hypercarbia.

SELFMIX CLOSED-CIRCUIT

Many versions of self-contained closed-circuit mixed-gas rebreathers have been developed in the past 25 years. They "self-mix" the respiratory gas from two gas bottles, one of inert gas, usually helium, and the other of pure oxygen. With continuously improving technology the earlier need to have an electronics engineer on hand to keep it going has given way to a remarkable reliability. A constant partial pressure of oxygen, around 0.7 bar, can be monitored by sensors and maintained at any depth. Duration is limited only by the capacities of the gas supply bottles and the duration of the scrubbing system. This type of apparatus has good breathing characteristics in the water and should maintain the inspired gas within defined physiological limits.

In the North Sea every diver must have a reserve "bail-out" gas supply so that he can get back to the bell if his primary breathing apparatus fails. In fact the duration of any diver-carried open-circuit system is likely to be limited to only a minute or two at great depths. In consequence self contained closed-circuit systems, such as the Rexnord, have been provided as bail-out systems for hose-supplied divers.

For the recreational diver a closed-circuit apparatus provides extended duration at any depth without the need to carry large volumes of gas. Reliable sets should provide reasonably warm breathing gas and few problems. These sets should be physiologically as safe as one could wish and only if the technology fails would the diver be exposed to the hazards of hypoxia, hyperoxia or hypercarbia. Only problems like the high pressure nervous syndrome (HPNS) and safe decompression, which are unconnected with the breathing apparatus, will limit their potential at the deeper recreational depths.

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