Rebreathers

Steve Goble

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Scuba, technical diving, rebreathers/semi-closed, rebreathers/closed, mixed gas

Abstract

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Rebreathers are rapidly becoming the equipment of choice for many technical divers and others who feel that they offer some diving advantages. Far from being something new, rebreathers are the oldest type of self-contained underwater breathing apparatus. In the past, most of their development and use has been based around the needs of the military, and a number of the more complicated recreational rebreathers are based on military equipment. A rebreather generally consists of a counterlung, carbon dioxide scrubber, oxygen cylinder, and a cylinder of diluent gas. It can be fully a closed circuit or semi-closed circuit and utilise either pendulum breathing or a loop breathing circuit. Rebreathers subject their users to the risks of hypoxia, and oxygen and carbon dioxide toxicity, and require strict adherence to routines and safe diving practices.

Introduction

Rebreathers have been available to recreational divers for a number of years. While their use in Australian waters has so far been limited by the value of the Australian dollar, there has been a rapid growth in their use in Europe and the USA. This has inevitably led to accidents, including a number of fatalities, in those areas. While accidents involving rebreathers are not yet showing up in the Diving Incident Monitoring Study (DIMS), Project Stickybeak, or Diving Emergency Service (DES) data, at least one near fatality and a neurological decompression illness case have occurred in Australasia during the last twelve months. Given the growth in the use of rebreathers, it is inevitable that at some stage doctors who deal with divers are going to be presented with a sick diver who has been using a rebreather. It is important that these doctors at least understand the principles of rebreather operation and the most common adverse events associated with the use of rebreathers.

The rebreather is the oldest form of self-contained underwater breathing apparatus (scuba). Probably the first recorded instance of its successful use was Lambert's entry of a flooded tunnel under the River Severn wearing an oxygen rebreather designed by Fleuss for mine rescue.[1] Despite this success, development of the rebreather was slow until World War Two. During that war, Italian Navy divers successfully used 100% oxygen (O_2) fully closed circuit rebreathers to attack Allied shipping at Gibraltar and Alexandria. After the Italian surrender, the British Royal Navy (RN) worked with the Italians and began its own development of rebreathers for use with O_2 and nitrox. After the war, some early recreational divers used war-surplus O_2 rebreathers. However, by the mid 1950s the open circuit demand valve had become much more popular, due to its ease of use, and the continued use and development of rebreathers were left mostly to the military.

Rebreathers come in a few basic types. They can utilise either pendulum breathing, in which the diver's breathing gas passes through a carbon dioxide (CO_2) absorbent ('scrubber') on inhalation and exhalation, or a loop circuit, in which the gas passes through the absorbent in one direction only. They can utilise either 100% O_2 or mixed gas, or both. They can be semi-closed circuit (produces bubbles and uses a constant gas flow) or fully closed circuit (no bubbles, uses a demand valve).

Clearance Divers Breathing Apparatus (CDBA)

The RN's Clearance Divers Breathing Apparatus (CDBA) is probably the most highly developed rebreather using the pendulum system of operation (Figure 1). This system incorporates a single breathing hose, with the scrubber located between the hose and the counterlung. The advantages of this system are several, among them: no one-way mushroom valves; increased scrubber efficiency due to the granules of scrubber media being presented to the gas on both sides of the grain; and simplicity of design. Disadvantages include the need for the diver to be aware that shallow breathing patterns will result in rebreathing gas that has not fully passed through the scrubber.

The CDBA is a complex system that was designed for heavy-duty use by military divers. It relies on a constant mass flow of gas, which can be either a nitrox mixture or 100% O_2. It contains an integrated weighting system, a bypass valve system, and an emergency gas supply in addition to the main cylinders. The counterlung is constructed of moulded rubber and has a capacity of 8 litres, it carries the scrubber and a relief valve, and is fabricated as an integral part of the front harness. The harness also carries two mounting pockets for the oxygen cylinders.

The scrubber is located centrally in the counterlung, directly under the diver's chin. It is modest in size, holding slightly

FIGURE 1. CIRCUIT DIAGRAM OF THE BREATHING SYSTEM OF THE CDBA IN SEMI-CLOSED CIRCUIT MODE.

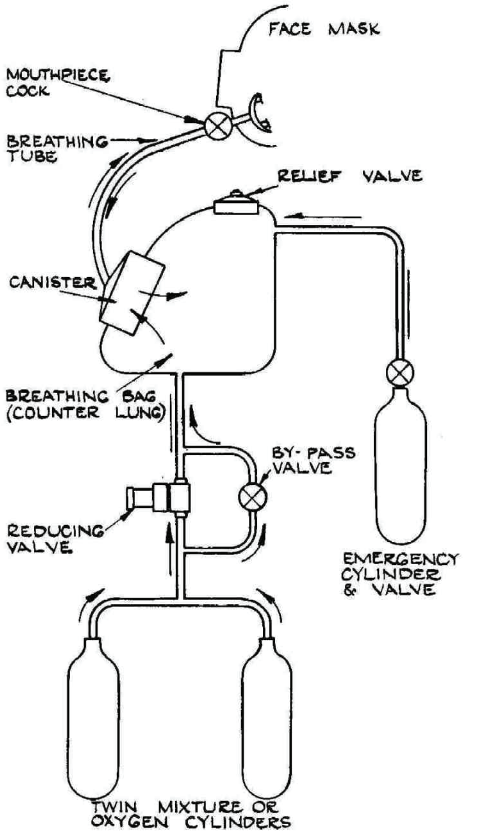


FIGURE 2. CDBA DIVER DRESSED FOR OXYGEN SWIMMING

less than one kilogram of CO_2 absorbent. This is partially compensated for by the superior efficiency of the pendulum system as described earlier. To the scrubber is attached a single breathing hose, a full-face mask and a dive/surface valve, which has two positions. One allows breathing from the counterlung through the scrubber, the other breathing from the atmosphere. Breathing in from the counterlung then switching the valve and breathing out to the atmosphere allows a dressed diver to expel gas from the counterlung to the atmosphere during pre-dive procedures.

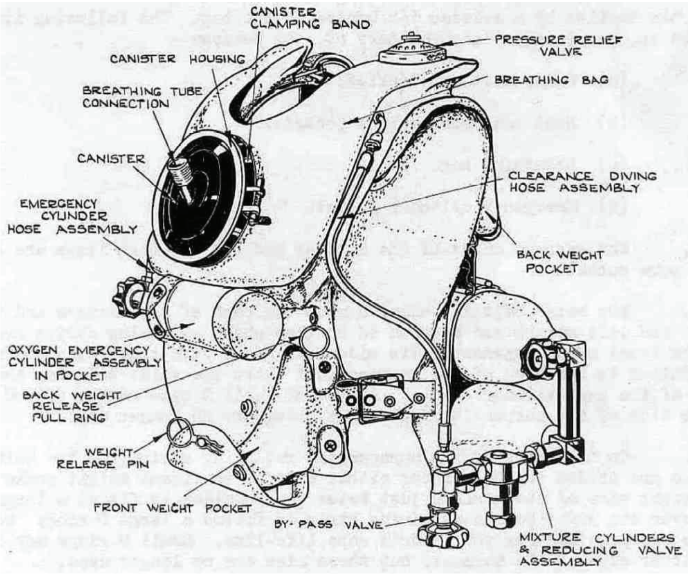
The reducing valve is a constant mass acoustic jet regulator, with a bypass valve, which supplies a constant flow of gas to the counterlung. Prior to diving, the required gas mixture is determined and the flow is adjusted accordingly. Once the flow is set, and the equipment is ready for use, the adjusting mechanism is no longer accessible making it impossible to adjust in the water. The regulator is industrial in nature, with all components being oversized and constructed of heavy brass billets machined to shape.

When the CDBA is rigged for oxygen swimming in semi-closed circuit mode, the twin oxygen cylinders on the front carry 147.6 litres of oxygen at 3000 psi (20×10^3 kPa). With the regulator flow set to 1.5 $l.min^{-1}$ for oxygen swimming, the cylinders have an endurance of 98 minutes. However, the endurance of the set is limited to 90 minutes by the life of the CO_2 absorbent. The weight pouch on the back harness contains lead balls, each weighing approximately 0.3 kg, which allows for reasonably precise weighting. Figure 2 shows a CDBA diver dressed for oxygen swimming.

Operationally, the twin O_2 cylinders are used as bail out for nitrox swimming; they are turned around in their pouch and connected to the right-hand side of the counterlung. The nitrox cylinders are filled with one of three different nitrox mixes and the regulator flow is set according to the mix being used. Figure 3 shows the CDBA set up for mixed gas diving. Maximum depth is 54 msw and the maximum partial pressure of oxygen (ppO_2) is 204 kPa (2 bar). In reality, the maximum ppO_2 was rarely reached, even at the respective mixes' maximum depths, due to dilution of the breathing gas in the counterlung by exhaled gases.

Possibly the most dangerous way to use the CDBA is in fully closed circuit, 100% O_2 demand mode. When in demand mode the regulator is not used, the cylinder is connected directly to the counterlung, and the diver manually adds O_2 when the counterlung is empty, being careful not to put in so much that the relief valve opens.

FIGURE 3. CDBA MIX SCHEMATIC



The CDBA is very popular amongst the clearance diving fraternity. It is comfortable to wear, there is no cylinder down the middle of your back, no bulky buoyancy compensator, and it requires very little weight. It is quiet, there are no bubbles blasting past your ear, just a gentle hiss from the regulator and a few quiet bubbles from your left shoulder. It is non-magnetic, the cylinders are aluminium and all other fittings are brass. This, and the lack of noise make it an ideal piece of equipment for mine countermeasures. In demand mode there are no bubbles at all, making the CDBA ideal for clandestine operations.

On the downside, it requires a great deal of training to learn to dive using this equipment. In the RN, we did four weeks of open circuit air diving, two to three dives per day, five days per week on scuba and surface supply before we were allowed anywhere near a rebreather. Basic rebreather training lasted four weeks, two weeks of O_2 swimming, and two weeks of nitrox diving. It took a few years to gain enough experience to use the CDBA in 100% O_2, closed circuit demand mode.

Gas toxicities

Rebreather equipment requires that divers maintain a rigid adherence to routines. There is a set procedure to follow before and during the dive. On reaching bottom, and before any depth change, the counterlung must be filled with fresh gas via the bypass valve. If the counterlung is not filled with fresh gas before any movement to shallower water, the ppO_2 in the counterlung will drop during the ascent. This leads to dilution hypoxia and the end result is usually an unconscious diver.

Apart from dilution hypoxia, divers using rebreathers are prone to two particular gas toxicities. Working with a maximum ppO_2 of 202 kPa (2 bar) means that central nervous system O_2 toxicity is a constant threat. Maximum depth limits have to be strictly adhered to. Modern recreational rebreather practice is to work with a maximum ppO_2 of 140 kPa (1.4 bar).

Carbon dioxide (CO_2) toxicity is the other gas toxicity associated with rebreather diving. When working hard, it is possible to breathe so hard and fast that the absorbent cannot keep up with demand and a CO_2 build-up occurs. Badly packed scrubber canisters or shallow breathing can also cause this problem.

Dräger LARV

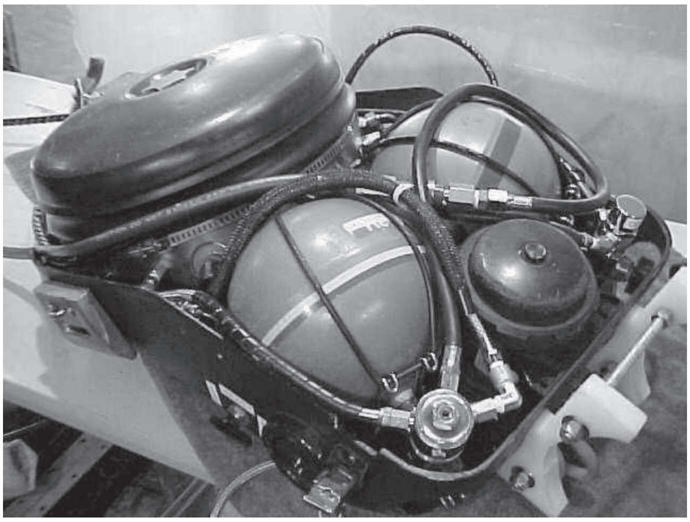
Eventually, rebreather designers took advantage of the second stage demand valve allowing for loop circuit, fully closed circuit rebreathers, such as the Dräger LARV oxygen rebreather. This is essentially purpose-built for combat swimmers, and is used by navies around the world. It is a very popular and well-built unit.

In the LARV's breathing loop, the diver's exhalation hose feeds directly into the counterlung. From the counterlung, the gas passes through the CO_2 scrubber and into the diver's inhalation hose. In the centre of the counterlung is an automatic/manual addition valve that provides the loop with oxygen. This valve is essentially a second stage demand valve; breathing in against a collapsed counterlung forces the tilt valve to operate and fresh oxygen is fed into the counterlung. Pressing the manual addition button is like pressing a purge valve. This is the most simple configuration possible for a rebreather loop.

Electrolung

While the use of second stage demand valve technology enabled fully closed circuit oxygen systems, mixed gas

FIGURE 4. BIOMARINE MK 15 IN RECREATIONAL DIVING SET UP



rebreathers still relied on constant mass flow and semi-closed circuit equipment. As solid state electronics got better and oxygen sensor technology improved, designers started looking at electronically controlled, fully closed circuit, mixed gas rebreathers.

One early version was the Electrolung, which made an appearance in the late 1960s and early 1970s, and was used for a while in the offshore diving industry as the dive equipment on diver lock out submersibles. Further development was stalled when the Health & Safety Executive in the United Kingdom decreed that a diver's main gas supply must be supplied from the surface. This effectively ruled out further rebreather development for the offshore oil industry.

Biomarine Mark 15 and 16

In the late 1970s, Biomarine in the USA, in conjunction with the US Navy, started development of an electronically controlled, fully closed circuit, mixed gas rebreather capable of using heliox mixtures to extreme depths. In Figure 4, we see the Biomarine Mk15 electronically controlled, fully closed circuit, mixed gas rebreather with the casing removed. This is the rebreather against which all others are measured. Currently, the US, British and Australian navies use a later version, the Mk16. Modifications for civilian use have included the addition of a utility bottle and a manual three-way valve.

The Mk15 and Mk16 are controlled by three oxygen sensors of the micro fuel cell type which, in conjunction with a small computer, maintain a preset ppO_2. If two sensors fail, the rebreather converts to a diluent loop with fresh diluent gas supplied to the counterlung. Removing the back cover exposes the CO_2 scrubber and the two gas spheres (Figure 4). One sphere is filled with pure O_2, the other with a diluent mix of either heliox or air. Spheres are used as they can be filled to higher pressures than cylinders, allowing for greater endurance.

Inside the cover of the CO_2 scrubber is an absorbent foam inset that absorbs water vapour, drool etc., from the exhaled gas. In the centre of the scrubber, the three oxygen sensors (micro fuel cells) are held in brackets at a 120-degree angle to each other. The different orientations of the faces of the sensors assist in preventing their blockage by water vapour. As the sensors are located out of the main gas-path, they are exposed to less than the total volume of water vapour present, yet they are in a position where each breath passes a sample of gas over their faces. This makes the design of the Mk15 resistant to condensation-induced oxygen sensor impairment.

The counterlung of the Mk15 is essentially a giant demand valve. Breathing in hard against the diaphragm pulls it down against the diluent addition valve and diluent gas is added to the counterlung.

A 'primary' display shows the breathing loop's ppO_2, as compared to the setpoint of the rig, in a very simple fashion. For a rig set at 1.4 bar (143 kPa) ppO_2, a green 'O' in the centre is illuminated when the rig is at 'setpoint'. Yellow '1' indications to either side of the 'O' are for slightly high and slightly low ppO_2 levels. Red alarms 'L' and 'H' at either end of the display indicate a serious low or high deviation from the setpoint. An 'A' shows the status of the sensors, being illuminated when a sensor is voted out by the digital electronics. Although called the 'primary' display, this is really just a crosscheck on the computer.

There is also an analogue 'secondary' display, which is really the primary method of monitoring the ppO_2 of the system. This is merely a millivoltmeter that reads the raw output from all three sensors. The scale on the face of the meter is calibrated in ppO_2, and the display is calibrated to new cells as they are installed. There is a rotary switch on one side that is used to select cell 1, 2, or 3 for viewing and can also be used to read the battery condition.

Straight up is the position of the needle that you want to see. The display is viewed periodically and the three sensors compared. If the primary display shows one sensor has been voted out, the secondary display can be used to confirm the failure. In the event of two sensors failing, a loop-flush with diluent gas is performed, and if the diver knows what the diluent ppO_2 should be at the present depth they can identify the remaining good sensor.

When the Mark 15 is set up for civilian use, a manual diluent addition valve is added, as well as a selector valve for diluent feed. This allows selection of a second diluent source for gas changes mid-dive. This configuration allows for a descent on air, a switch to heliox diluent at a precalculated depth (this makes a 'trimix' in the loop), and the reselection of air on ascent. With the loop then purged and refilled, a nitrox decompression can begin. At seven metres' depth, the valve can be positioned at the mid position, shutting off the diluent and allowing a pure oxygen operation to be conducted for final decompression. This works very well and is a tried and tested system.

As with all rebreathers, there is no facility to measure CO_2 levels. The diver has to accept that he has filled the scrubber correctly and there is no channelling, also that it was filled with fresh absorbent and has not been sitting around unsealed. Filling the scrubber properly requires meticulous care and attention.

Although modern solid-state electronics are very reliable and sensor technology has improved over the two decades it has taken to reach this stage of development, there are still drawbacks to using these rebreathers. A fully charged military version Mk15 weighs 29 kg and, as it is positively buoyant, a weighted diver carries around 40 kg. If rigged with an extra gas cylinder, as described earlier for civilian use, the weight increases even more. This is not the kind of equipment you want to run around with. Furthermore, diving with rebreathers does not come without a cost. The civilian version of the Mk15 costs around A$20,000 dollars, more if you want two diluent gas spheres and other extras.

Conclusions

In summary, the rebreather can be a useful tool for a few specific tasks:

- Combat swimming or espionage in the closed circuit 100% oxygen mode. The next person exiting a submarine to swim to shore wearing a closed circuit oxygen rebreather will not be the last.
- Mine countermeasures. These units are very quiet and made of non-magnetic materials – two qualities that are ideal for dealing with mines.
- Photography. The lack of bubbles or noise makes the units ideal for approaching fish.

In recreational diving circles, technical ('tech') divers are using fully closed circuit rebreathers to undertake extreme wreck and cave diving, where the long endurance and extreme depth capability allows them to penetrate to areas previously unreachable. However, the limitations discussed previously remain – gas toxicities, oxygen or carbon dioxide. Hypoxia is still an insidious effect of ascent. The use of all rebreathers, whether closed or semi-closed, requires a high degree of training and experience, and high skill levels. You need to know your equipment inside out and be completely familiar with its integral parts.

While the high cost of the more sophisticated rebreathers such as the Mk15 puts them into a very dedicated level, there are available lower cost nitrox units utilising more of a semi-closed circuit. These are increasingly popular with 'tech' divers. In the next decade, we can expect an upsurge in recreational rebreather diving and its associated medical problems.

Acknowledgement

Dave Sutton for permission to use photos from his website <www.nobubblediving.com>

Reference

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Steve Goble is Head Hyperbaric Technical Officer at the Hyperbaric Medicine Unit,
Royal Adelaide Hospital, North Terrace, Adelaide,
South Australia 5000, Australia.
***Phone:** +61-(0)8-8222-5514*
***Fax:** +61-(0)8-8232-4207*
***E-mail:** <sgoble@mail.rah.sa.gov.au>*

Deep air and mixed gas recreational diving accidents from the UK

News item, Diver Magazine, October 2002

Two divers lost their lives in separate incidents in August.

On 18 August, an incident off Brighton left a diver dead and his brother injured. The pair made a rapid ascent while diving the 48m-deep *Pagenturn,* 12 miles off Brighton. Solent Coastguard said that they appeared to have encountered difficulties while deploying a delayed SMB.

Graham Law, 40, from West Sussex, surfaced unconscious. Resuscitation attempts were made on the dive boat *Girl Gray,* but Law was pronounced dead after being airlifted to Brighton Hospital. Law's equipment is being examined at the Health & Safety Laboratory for the coroner.

His brother Richard, from Surrey, was taken aboard the dive boat with decompression illness. He had to be airlifted to Whipps Cross Hospital in London as, according to skipper Mike Snelling, 'all the chambers on the South Coast were full' that weekend.

The second fatality occurred a day later, when a diver appeared at the surface feet-first after a rapid ascent from a mixed-gas dive, 24 miles out from Littlehampton.

Peter Downes, 47, described as an experienced Advanced Instructor, was diving with Mendip Dive Club, from near Bristol. He is reported to have surfaced from a 28-minute dive to 66 m without making any stops. Downes was still attached to an underwater scooter on reaching the surface. Both this and his dive gear were lost during his recovery on to the dive boat *Voyager,* but his drysuit and computer were sent for examination by the Health & Safety Laboratory.

Attempts were made to revive Downes before he was airlifted by Solent Coastguard to Portsmouth's Queen Alexandra Hospital, where he was pronounced dead.

One of the many South Coast recompression treatments carried out on 18 August was to a diver lucky to escape death or injury after surfacing unconscious from a mixed-gas dive to 70 m off Brighton.

The diver is reported to have suffered a convulsion after selecting an incorrect (oxygen-rich) decompression gas at about 30 m. He was sent to the surface by his buddy. Recovered unconscious onto the dive boat *Spartacus*, he was airlifted and reportedly recovered fully after recompression treatment.