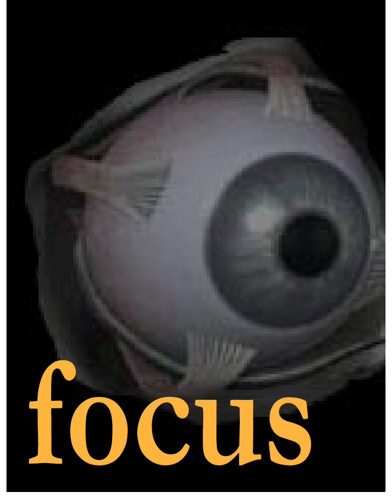

Contrary to popular belief rebreathers are actually a much older scuba diving technology than open circuit regulators

The Long (his)Story About
Scrubbers & Sensors
From Fleuss to Evolution

Text: Michel Tagliati
Additional reporting by
Peter Symes

There is more and more talk of rebreathers, stated as being the future of diving. However, not many people have tried them. So what is all the fuss about?

The greatest majority of the readers of this magazine will have learned to dive with a regulator originating from the Aqualung, which the renowned Jacques Cousteau and Emile Gagnan invented in 1940. The regulator was the first commercial, generally available dive-system, and this promoted the later great expansion of sports diving everywhere. And it must be said that the regulator is a fine piece of equipment. It is reliable, more or less foolproof, and its simple construction is very robust. These are good properties to have when one's underwater breathing depends on them. However, as we will see, there are also a number of disadvantages. And it is these that make re-breathers an interesting alternative system.

When diving with a regulator, it is said that one is diving with an *open circuit*, because the exhaled air passes straight out into the surrounding water, and is thereby lost. As only about a quarter of the available oxygen has been taken up by the body, and the rest expelled, it is a rather ineffective utilisation of a scanty resource. (See table next page.)

In addition, as the amount of air used increases proportionally with depth, open systems become more and more inefficient, and there are therefore major limitations to how long a diver can remain underwater. It seems obvious, then, to try to re-use the air that has been exhaled, by using a closed system.

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Ambient Pressure Diving's Closed Circuit Rebreather *Evolution* is the latest step in CCR ...erh... evolution.

Closed circuit systems

Closed circuit systems are a far from new idea. It was Giovanni Borelli in the 1700's who first thought of re-using the exhaled air. His idea was to recirculate the air through a copper tube which was cooled by the sea water, and thereby "cleaned" the air before re-use. Luckily, it was never made. The mining industry and its problems with gas in the mine shafts also stimulated the relevant technical developments during the 1700's.

Henry Fleuss, an English naval officer from Germany, worked out the principles for a re-breathing apparatus, and produced a prototype at the end of the 1870's. He stayed down in a water tank for nearly an hour, and later went down to 5 meters in a lake using his system. Fleuss was the first "diver" in history with a re-breathing apparatus. At the beginning of the 1900's the military were quick to take up this idea. Oxygen-rebreathing equipment consisted of an oxygen tank together with a bag of potassium hydroxide and a breathing loop, and was used to rescue submarine crews and attack divers (there were no revealing bubbles on the surface). The German manufacturer Dräger released several models for military use in connection with World Wars I and II.

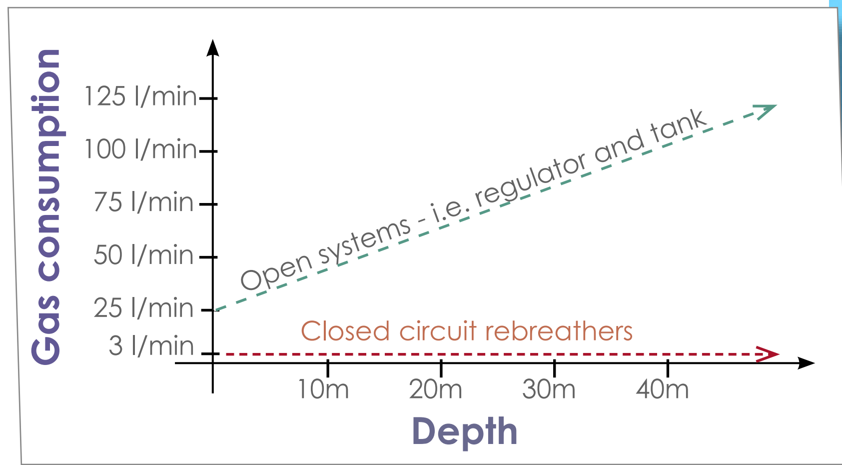
Respiration

In a modern medical textbook on physiology, one of the several chapters on aspects of respiration is entitled "Physical principles of gaseous exchange; diffusion of oxygen and carbon dioxide through the respiratory membrane". And it is these very important principles that are of great interest to divers. How we take in and utilise oxygen, and how we get rid of the carbon dioxide produced by metabolism.

Cellular metabolism is independent of pressure

The amount of air which is needed to take a normal breath at a depth of 20 meters is three times greater than at the surface, and therefore the consumption of air with open systems increases with depth. **However, more importantly, cellular metabolism does not depend on the pressure.**

Oxygen is required to make adenosin trifostat, ATP, the fuel of the human cell. And a molecule of oxygen is a molecule of oxygen, wherever it is to be found, at the beach, or 100 meters deep, with the corresponding increase in pressure. Therefore, when using a closed circuit there is the same consumption of air, whatever the depth. At rest, 0.3 to 0.5 liters of oxygen are used per minute (l/min), and with maxmum work up to 3.0 l/min are used. Of course, there are differences between individuals, depending on the size of the diver and his or her physical condition.



Comparison of gas consumption in open and closed systems. In closed circuit rebreathers the gas consumption doesn't vary with depth.

The carbon dioxide problem

As we have seen, cellular metabolism depends on oxygen, which is inhaled from the atmosphere. The following table gives the composition, in volume percent, of inhaled atmospheric air (on an average cool, clear day), and also the corresponding composition of exhaled air. (There is also a minor content of the non-reactive noble gases such as argon, helium, etc., but this has been ignored here.) It will be seen that the uptake of oxygen in the lungs has caused the oxygen content of the inhaled air to be reduced from its original 20.84% to 15.7% in the exhaled air. It will also be seen that the concentration of carbon dioxide, a biproduct of metabolism, has *gone up by about ninety times*, to 3.6%.

COMPONENT	INHALED AIR %	EXHALED AIR %
N_2	78.62	74.5
O_2	**20.84**	**15.7**
CO_2	**0.04**	**3.6**
H_2O	0.50	6.2
Total	100.0	100.0

So, it is not so much the reduction in amount of oxygen that is the problem, for there is still some 16% available in each expelled breath, which should be available for re-use. It is the increase in carbon dioxide, CO_2, that is the real problem. A diver can tolerate a build up to a CO_2 concentration of about 10%, increasing respiratory volume to compensate for the increased CO_2. However, beyond the 10% level the respiratory center in the brain stem begins to be depressed rather than stimulated, and the diver's respiration then actually begins to fall rather than to compensate. As a result of this, varying degrees of lethargy, narcosis, and, finally, anesthesia will occur. The CO_2 in the exhaled air must therefore be removed before the remaining oxygen can be re-used. Luckily, this is quite easy to do, using calcium hydroxide, $Ca(OH)_2$, which reacts with, and therefore fixes, the carbon dioxide. It is called CO_2-*scrubbing* and the filtering material, in this case teh calcium hydroxide, which comes as a granulate, is referred to as the *scrubber*.

In a rebreather, CO_2-scrubbing therefore takes place by circulating the breathing gas through a canister with the scrubber granulate in it.

Scrubber, in this case Sofnolime, comes in small granules,

No, rebreathers are not new. In this 1912-footage we see Drägers helmet diving rebreather in use.
Photo: Dräger's archive.

Expression: Breathing loop
The whole volume of circulating gas in a rebreather, mainly the hoses, one or two counterlungs and also the diver's lungs.

A REBREATHER TIMELINE

1500´s In England and France, full diving suits made of leather with metal helmets. The diving helmets were already some sort of rebreather, but needed surface supply and were without scrubber

1680 Giovanni Borelli designed a closed breathing circuit. The idea was to recirculate air through a copper tube which was cooled by sea water. The assumption was that al the impurities would then condense out of the air inside the tube.

1726 Stephen Hale designed the first scrubber: a flannel liner, soaked in salt and tarter, used in a helmet for mine disasters.

1772-4 Oxygen independently discovered by Swedish chemist, Carl Wilhelm Scheele, in 1772, and the English chemist Joseph Priestly, in 1774. Soon followed the first known ideas to use Oxygen for diving and first functional ideas to build autonomous rebreathers.

1876 Henry Fleuss began to develop an oxygen rebreather. He used a rubber face mask and a breathing bag connected to a copper oxygen tank. The carbon dioxide, scrubber was a rope yarn soaked in a solution of caustic potash. Enabling Fleuss to walk along a river, this was the first SCUBA Dive.

1879 Fleuss builds a Mining-Rescue Rebreather for Siebe/Gorman

1881 A special rebreather scrubber using a barium hydroxide is patented by Khotinsky and Lake.

1904 Siebe and Gorman patent Oxylite, a potassium- and sodium-peroxide mixture that produces oxygen on contact with water.

1907 A Dräger rebreather is used as submarine rescue equipment

1912 Dräger helmet-diving-rebreathers are available

1913 Dräger performs a successful simulated 40 minute dive to 80m in chamber.

1914 Dräger introduce a selfmixing Nitrox-Rebreather for max. 40m.

1926 Dräger presents the first early recreational rebreather, the 'Bade-tauchretter'.

1941 Dräger "Kleintauchgerät 138"

1953 Dräger Leutnant Lund II and Barakuda Delphin I

1967 Russians experiments with predecessor to AKA-60

PETER SYMES

Lt.Lund rebreather, 1953

Scrubbers

Although easy to do in principle, getting a CO_2-scrubber to function in a safe and reliable way is not completely without its complications - which many divers have found out to their cost. As with walking or running, it takes work to breath underwater. If the resistance to breathing is too high, there will be physiological problems which will limit the use of this system.

Also, *hypercapnea*, the condition where there is too much CO_2 in the body can become an issue. The material used to remove the carbon dioxide in the system, the scrubber, has a limited life, and can only fix a certain maximum amount of carbon dioxide.

As these filters cost money, people are disinclined to change them often enough. The maximum limit for how long these filters should be used is thus some times transgressed, which increases the risk of accidents.

The matter with oxygen

And while we are at it, why not increase the oxygen level in the ínhaled air, even perhaps right up to 100% pure oxygen? This way we could also avoid breathing in nitrogen, which is the cause behind depth narcosis and decompression illness and give away with all concerns about decompression limits. If it only was so easy! The apparently paradoxical answer is that pure oxygen quickly becomes poisonous under pressure.

Partial pressure of oxygen

Assume that we have a mixture of gases. Then the total pressure of the mixture is equal to the sum of the pressures exerted separately by each of the individual components in the mixture. So, if the mixture we are considering is atmospheric air, we have:

$$P_{atmos} = PN + PO + PCO_2$$

Where

P_{atmos} is the atmospheric pressure
PN is the partial pressure of nitrogen
PCO_2 is the partial pressure of carbon dioxide
PO is the partial pressure of oxygen

Now, according to the ideal gas laws, as the components are all at the same temperature, the partial pressures must be proportional to the volumes of each gas present in the mixture. In the table given above, oxygen has an volume % of approximately 21 of atmospheric air. This means that its partial pressure is 0.21 of an atmosphere, or 0.21 bar. This is oxygen's contribution to the total atmospheric pressure.

So, at the beach, oxygen in the air has a partial presure of ca 0.21 bar. And if the diver is using compressed air at a depth of 10 meters, then the corresponding oxygen partial pressure is 0.42 bar (0.21 x 2 bar), at 20 meters it is 0.63 bar, at 30m its 0,84 and so forth. In the literature the partial pressure of oxygen is written as ppO_2.

The importance of pp02

When discussing respiration this is probably the most important parameter to be considered. Not only must the excess carbon dioxide be removed from the air, but the partial pressure of the oxygen must also be maintained at a reasonably constant level to ensure correct cellular metabolism.

Gaseous diffusion from the alveoli of the lungs to the pulmonary blood is determined by the partial pressure of the oxygen. The partial pressure determines the force exerted in diffusion through the pulmonary membrane.

In other and more plain words, it is the ppO_2 and not the O_2 % that determines whether we live or die.

Consequently, ppO_2 should be mainatained within a certain range to sustain life.

Normal ppO_2 (at sealevel) is, obviously, 0.21 as air contains 21% oxygen. If the partial pressure falls below 0.12 (12% oxygen at sealevel) most individuals will lose their ability to function. Below 0.10 bar ppO_2 they will lose conciousness and below that die from asphyxiation.

On the other hand, a prologued exposure to high ppO_2 leads to oxygen toxicity and the condition hyperoxia which manifests itself in sudden convulsions, which under water inevitably will lead to drowning. Therefore a ppO_2 of 1.6bar is usually considered the upper limit in recreational diving, and only for a limited time. And 1.3 bar the level not to exceed in general.

For these reasons it should be clear that maintaining the ppO_2 of the breathing gas within specific bounds is of utmost importance. It becomes, quite litterally, a matter of life and death.

Diving conventionally with compressed air on open systems, as most regular holiday makers do, controlling ppO_2 is usually not an issue as normal air only reaches a ppO_2 of 1.3 bar at a depth of 54m - far beyond where they should venture.

But as soon as we start tinkering and raising the O_2-content of our breathing gas, these matters change, as we are taught already at entry level Nitrox courses —such as PADI's Enriched Air Specialty, or the various Basic Nitrox courses offered elsewhere.

1968	First electronically controlled rebreather, the Electrolung.is marketed
1970	BioMarine CCR-1000
1972	BioMarine Mark 15
1975	Dräger LAR V
1977	BioMarine NM-6
1978	Interspiro ACSC
1982	Interspiro Oxydive
1984	Dräger Tieftauchsystem CCBS for operating depths of max. 600m
1985	AKA-60 (Russian)
1991	Dräger Newtsuit
1992	Interspiro DCSC
1995	Dräger SCR Atlantis (1998 renamed in Dräger-Dolphin)
1998	Buddy Inspiration
1999	Dräger-Ray
2001	Halcyon RB80, Cochran CCR and Mares SCR Azimuth
2004	Ambient Pressure Diving's Evolution

PETER SYMES

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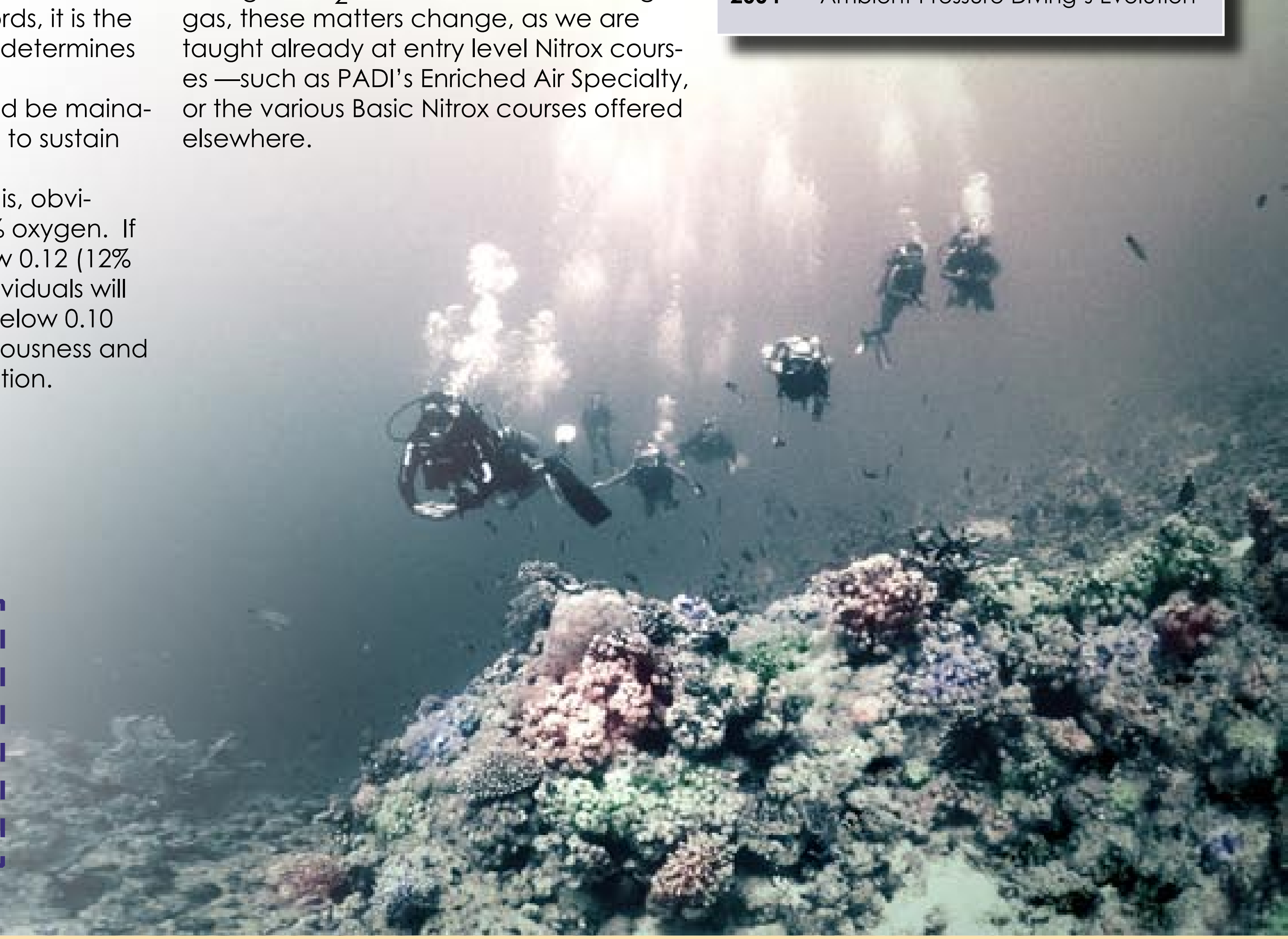
Oxygen rebreathers

In water pure oxygen rebreathers are restricted to use in shallow water of less than 6 meters - to keep ppO_2 below the1.6 bar limit. For this reason the pure oxygen rebreathers are of limited and mainly military use. Oxygen rebreathers however also have a use on land with firefighters, rescue crew and miners.



Whether we dive on open systems or semi-closed rebreathers (see explanation below) we chose, prior to the dive, our breathing gas with a predetermined oxygen-content. This may be air or we may op for another specific gas suitable for the depths we are aiming at. In most cases this will be Nitrox–which is now becoming quite a household word among divers.

Nitrox with 32 or 36% oxygen is now quite routinely being offered at divecentres, resorts and liveaboards worldwide as these two “standard-blends” will cover most needs in the typical recreational range with near optimum benefits.

However, chosing the right oxygen-% will always be a compromise between longer no-decompression times versus maximum depth. For example, diving on Nitrox with 36% oxygen gives a generous no-deco time of 50 mins at 26m - rather than the usual 20 min when diving on air. That is nice, but Nitrox 36 can´t take you any deeper, as pp0$_2$ is already 1.3 bar around that depth.

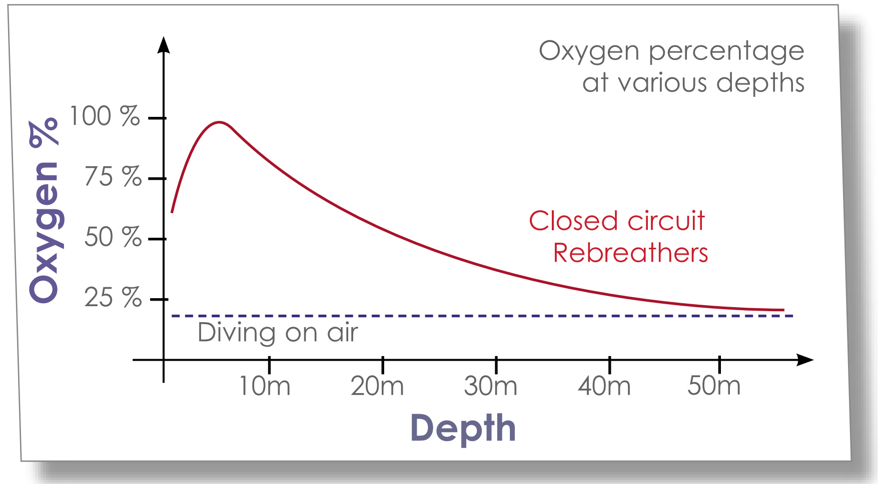
And if you dive any shallower you don´t get the full benefits of Nitrox at that particular oxygen content. So, for each depth there seem to be an optimum oxygen % in the breathing gas. With the current general limits, this optimum oxygen content corresponds to a constant oxygen partial pressure of 1.3 bar oxygen regardless of depth.

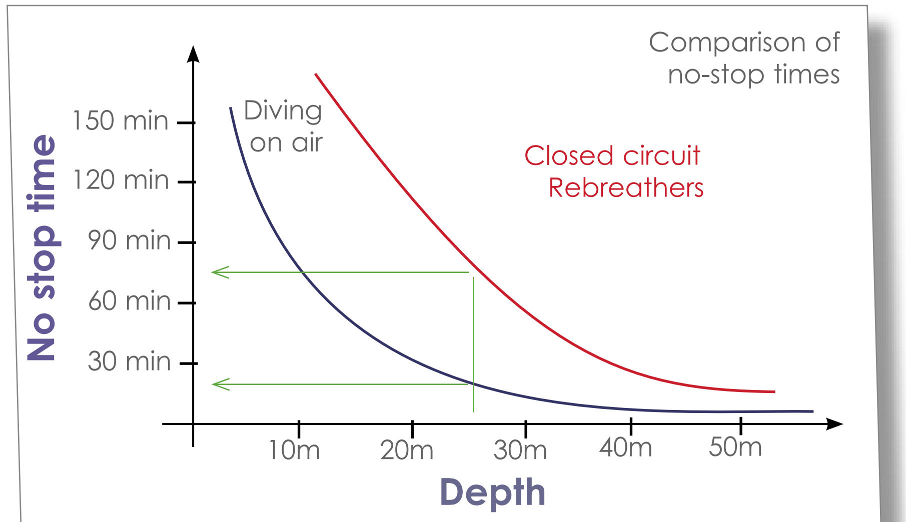
Controlling the pp0$_2$

To ensure that the correct oxygen level is obtained, i.e. its partial pressure, it is necessary to measure its concentration. For this purpose a special transducer is needed, *an oxygen sensor.* (see box below)

Modern closed breathing systems

With the advent of oxygen sensors and microprocessors, it is now possible to reduce the amount of gas taken down by a diver to a mere bagfull of atmospheric air and a few liters of compressed oxygen. These closed circuit rebreathers, CCR, use oxygen sensors to control the partial pressure of oxygen in the inhaled gas. This means that the diver can continually control and maintain oxygen partial pressure at certain levels during a dive. And this is where the fully closed rebreathers excel.





Say, for example, that a fullly closed breathing system has been set to maintain a given oxygen partial pressure at depth, typically 1.3 bar. If the diver then descends to another depth, the ambient pressure increases, and with it the oxygen partial pressure in the breathing loop. The rebreather then compensates to keep the oxygen partial pressure constant. Likewise, if the diver ascends, the pressure decreases, and the oxygen partial presure will decrease. The apparatus will then compensate in a controlled way by injecting some more oxygen into the loop.

As the graphs above clearly demonstrate, the potential extension of no-deco times are huge.

Open, semi-closed and fully closed circuits

By *Open Circuit* one usually refers to the omni-present regulator - a second and a first stage connected to on a tank of compressed air. The expression is partially misleading because the air doesn´t go in a circuit. It travels from the tank and via the regulator, through the diver before getting exhaled into the water in a one-way process.

A *semi-closed circuit* is a type of rebreather in which (most commonly) the breathing gas is being continously injected from the tank into the breathing loop where it circulates a number of times. On average the gas is re-circulated 4-5 times before being vented to the outside through an over-pressure valve. It is because gas is continously being vented that these circuits are referred to as being semi-closed (or rather semi-open). The breathing gases used in these semi-closed (circuit) rebreathers or ‘SCR’ are various preset Nitrox-blends. The popular Dräger rebreathers (Dolphin, Ray...) are SCRs.

In a *fully closed* (circuit) *rebreather* or ‘CCR’ all the gas is continuously being recirculated and no gas is vented. The CCR is generally being considered the thoroughbred of rebreathers. In CCR's the only gas being consumed is the oxygen metabolised by the diver (not considering gas used for inflating suits, wings etc and gas lost during ascent and decent).

Another important distinction between the popular Dräger SCRs and a CCR such as the Inspiration, is that the SCRs have a present oxygen-% and a variable pp0$_2$, whereas in the Inspiration it is the pp0$_2$ that is fixed and the oxygen-% which varies with depth.

Dräger Dolphin SCR

APD Inspiration CCR

Oxygen sensors

An oxygen sensor can be considered as a small fuel-cell in which the chemical energy of oxygen is transformed into electrical energy.

A very thin, plastic membrane, placed over the top of the sensor, operates as a solid barrier in which the oxygen molecules must dissolve in order to reach the sensing electrode. The flux of oxygen to the working anode is dependent on the partial pressure gradient of oxygen across the barrier. This means that the output signal from the cell is proportional to the partial pressure of the oxygen in the gas mixture.

When oxygen reaches the working electrode, it is immediately catalytically reduced to hydroxyl ions.

$$O_2 + 2H_2O + 4e^- = 4OH^-$$

These hydroxyl ions migr ate through a conductive electrolyte (typically potassium hydroxide) to the metallic lead anode, where they are involved in the oxidation of the lead to its oxide.

$$2\,Pb + 4\,OH^- = 2\,PbO + 2\,H_2O + 4\,e^-$$

So, as the two processes take place, a current is generated (represented here by the four electrons 4e-). This current can be measured externally by passing it through a known resistance and measuring the potential drop across it. Since the current produced is proportional to the rate at which these reactions occur, its measurement allows accurate determination of the oxygen concentration. The current produced can then be used, via a computer, to control an oxygen inlet valve.

As the electrochemical reaction results in the oxidation of the lead anode, these sensors have have a limited life. Once all the available lead has been oxidised they no longer work. Typically, oxygen sensors have 1 – 2 year life times.

Taking it further

Nitrogen is the usual diluent for oxygen in our normal atmosphere. However, as all divers know, nitrogen dissolves in the blood under high pressure, and can cause narcosis or decompression sickness. To reduce or eliminate this problem divers would like to use as little nitrogen as possible in the inhaled air.

Remove the biologically inactive nitrogen from the inhaled air and the risk of being hit by rapture of the deep disappears. And rebreathers can solve this problem, too, with the non-narcotic gas helium replacing nitrogen in the inhaled air being used at greater depths.

In CCRs like the Inspiration there are two tanks (see picture on previous page). One contains the oxygen which is being injected into to breathing loop to maintain the correct ppO_2.

The other tank contains the *diluent gas*, which usually is just air, but it can be anything breathable such as trimix. This gas is, basically, the 'base substance" of what you breathe and what the oxygen gets injected into, it is what inflates the breathing loop and what is used for buoyancy in the wing or drysuit. So with an octopus attached this tank also can double as a normal open circuit and as backup system should there be a problem with the rebreather. (Switching to open system by closing the rebreather's mouthpiece and breathing from the octopus instead is referred to as *bail-out*).

The diluent gas is normally not consumed except for what is used to inflate the breathing loop and maybe the suit and wing (some carry separate tanks for this, i.e. when argon is used for suit inflation).

For trimix divers this is very good news as Helium is a very expensive gas so using a rebreather also come a significant economic incentive. Also it means a significant reduction in weight and the number of tanks a diver who need to explore some extreme environments like deep wrecks and caves need to carry and for this reason the rebreather has become a preferred tool among many underwater explorers and scientists alike.

Next issue:

Diving the thing - what is it like and what the difference in skills?

"Now, where did that contact lens go?"

Disclaimer:
Diving with rebreathers requires special training.

When experience comes in the way

Diving with a fully closed system is, in many ways, significantly different from diving with an open system. Several things have to be re-learned, and re-learning is much more difficult if one has has long been used to diving with an open system. Many experienced divers think that they are quite competent at diving, and often find it difficult to accept that they are beginners again when diving with a completely closed breathing system.

For example, they may not realise that the oxygen partial pressure can vary considerably. Also, there is a risk that a very experienced diver will make serious elementary mistakes, due to a false feeling of safety. This can lead to a failure to carry out the vital control checks of the equipment before and after each dive.

Oxygen sensors degrade (oxidise) and must be changed every year, or more often, according to how much the system has been used. The reliability of the sensors and their output is also a matter of some controversy. It happens that technical divers use fully closed systems at depths of more than 100 meters, in spite of the fact that neither the equipment nor the sensors are approved for these depths because of the doubts regarding the reduced reliability of their performance. (see, for example, the story about David Shaws fatal dive to 271m in X-RAY #3)

But, today, it is technically possible to dive to a depth of 100 meters with a couple of 3-liter tanks containing 200 bars of compressed oxygen. However, the technique is so advanced that the necessary knowledge, training and maintenance of this equipment is not yet fully integrated into the training courses offered today.

To dive safely with fully closed systems requires a thorough theoretical and practical knowledge plus frequent use in order to maintain the routines and reflexes learned during training.

Water is unique in that it is the only natural substance that is found in all three states – liquid, solid (ice) and vapour – at the temperatures normally found on Earth

The Uniqueness of Water

Water, obviously, is essential to our very existence, without it we rapidly die. In spite of this, everybody perceives water to be a rather ordinary sort of stuff, as it is transparent, odourless, and tasteless.

Many divers feel almost just at home in water as they do in air, and rarely, if ever, think about its more unusual physical properties. Water appears to be a very simple molecule, consisting of just two hydrogen atoms attached to an oxygen atom. There are, in fact, very few molecules that are smaller or lighter. In spite of this, it is a most remarkable substance, with many anomalous properties.

For a start, water is unique in that it is the only natural substance that is found in all three states – liquid, solid (ice) and vapour – at the temperatures normally found on Earth. And the fact that ice and liquid water can coexist at the not abnormal temperature of 0°C, is extremly important for all life on Earth.

Water has an unusually high density, and this density is further anomalous in that, unlike other liquids, it increases on cooling down to **3.984°C a**nd then decreases until the freezing point temperature of 0°C is reached. The density of water is thus a maximum at about 4°C, meaning that it expands both on heating and cooling from this temperature. This density maximum, together with the low ice density, ensures that all of a body of water (not just its surface) must be close to 0°C before any freezing can occur. The freezing of rivers, lakes and oceans is therefore from the top down, so insulating the water from further freezing. The oceans do not, therefore, freeze from the bottom upwards until they result in just a thin layer of liquid water on solid ice. If they did then life as we know it today could not have been possible.

The unusually high density of water is mainly due to the cohesive nature of the hydrogen-bonded network. This reduces the free volume and ensures a relatively high-density, compensating for the partial open nature of the hydrogen-bonded network. Why the density of water actually has a maximum at 4°C requires a much more detailed thermodynamic explanation than can be given here. ■