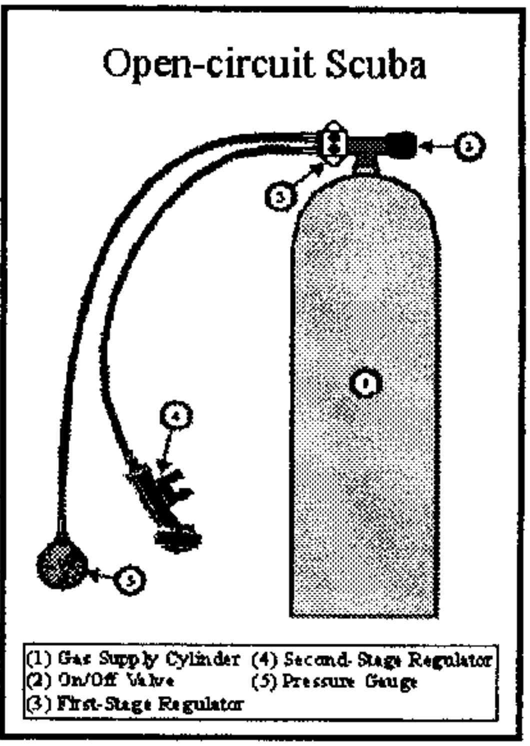
What is a "Rebreather"?

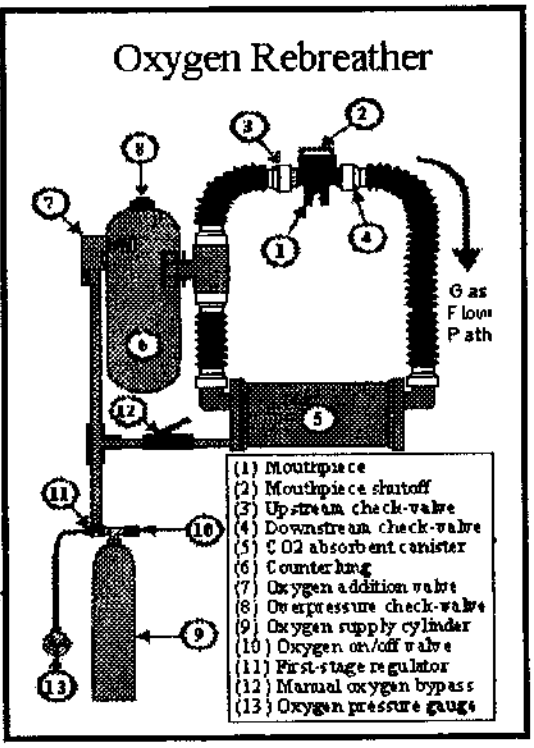


To understand what a rebreather is and how it works, it is useful to understand how conventional scuba works. Nearly all diving apparatus presently available to the public falls into a class known as open-circuit scuba. This type of system (picture at right) was first introduced to recreational divers by Cousteau and employs a compressed gas supply and a demand regulator from which the diver breathes. The exhaust gas is discarded in the form of bubbles with each breath, hence the term "open-circuit". Open-circuit scuba is inherently inefficient: because only a small fraction of each inhaled breath is actually used by the diver for metabolism, there is a tremendous waste of useable *oxygen* (O_2) with each breath. Furthermore, the quantity of O_2 lost in this manner increases with increasing depth.

A rebreather is a fundamentally different kind of diving apparatus. There are three basic types of rebreathers presently being used in government and industry: *oxygen* rebreather, *semi-closed* rebreather, and *closed-circuit* rebreather. Each has specific advantages and disadvantages, as will be discussed briefly below. All kinds of rebreathers, however, have certain basic components in common. All designs start with a *breathing loop* equipped with a *mouthpiece*, through which a diver breathes. If the entire breathing loop is of rigid construction, the diver would be unable to breathe because there would be nowhere for the exhaled gas to go into, nor the inhaled gas to come from (analogous to trying to breathe in and out of a soda bottle). Thus, there must be some sort of collapsible bag attached to the breathing loop that inflates when a diver exhales, and deflates when a diver inhales. This bag is referred to as, appropriately enough, a *counterlung*. If a diver were to continue breathing in and out from this breathing loop, the *carbon dioxide* (CO_2) exhaled by the diver would soon build up to dangerous levels. Therefore, the breathing loop must also include a *CO_2 absorbent canister* containing some sort of chemical (e.g., HP Sodasorb, Sofnolime®, or lithium hydroxide) that absorbs CO_2, removing it from the breathing gas. Of course, the CO_2 absorbent canister alone will not permit the diver to continue breathing from the rebreather indefinitely; the oxygen in the breathing loop will eventually be consumed by diver via metabolism. Therefore, the rebreather must have some means to allow oxygen to be injected into the breathing loop in order to continue sustaining the diver. Furthermore, to prevent the diver from simply inhaling the same gas that was just exhaled, the rebreather must be designed to ensure that gas continues to circulate in one direction around the breathing loop. This is usually accomplished with an *upstream check-valve*, and a *downstream check-valve*, located on either side of the mouthpiece; these allow inhaled gas to come from only one direction in the breathing loop, and allow exhaled gas to go only in the opposite direction. Another feature common to most rebreather designs is some sort of shut-off valve in the mouthpiece which can be shut if the mouthpiece is removed underwater, to prevent water from flooding the breathing loop.

The fundamental difference between the three kinds of rebreathers is the way in which they add gas to the breathing loop, and control the concentration of oxygen in the breathing gas.

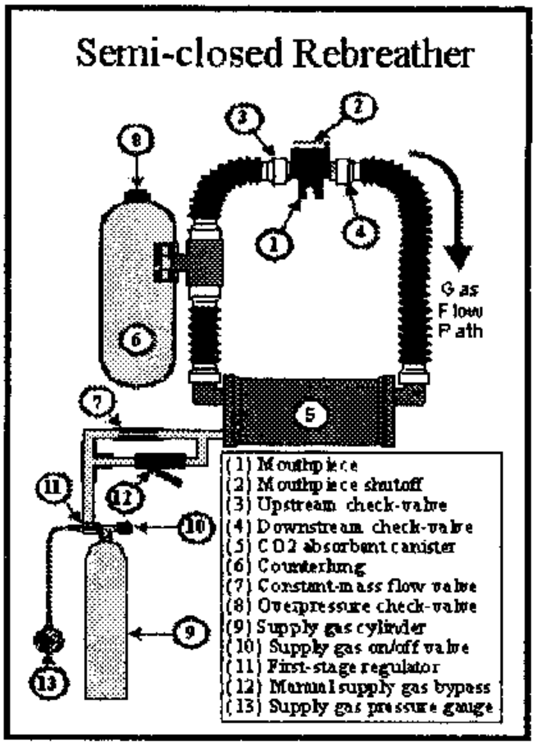
Oxygen Rebreather



The oxygen rebreather is the simplest kind of rebreather system, and will form a starting point for discussion of more complex systems. An oxygen rebreather consists of the basic components described above, with a cylinder of pure oxygen as the supply gas to replace the oxygen consumed by the diver. Some types of oxygen rebreathers add oxygen into the breathing loop at a constant rate, which is chosen to closely match the rate at which the diver's metabolism consumes it. However, the diver's rate of metabolism may vary during the course of the dive due to variations in the diver's workload. Hence, such an *active-addition* system is prone to adding too much oxygen during periods of rest (resulting of wasteful venting of gas from the breathing loop), and/or not enough oxygen during periods of heavy work (resulting in the need for the diver to add oxygen via a manual bypass valve). Many oxygen rebreathers incorporate some sort of *passive-addition* system, whereby oxygen is added to the breathing loop at a rate that matches the metabolic consumption rate of the diver. A simple method for achieving this sort of gas addition system involves a mechanical valve which is triggered when the counterlung is completely collapsed. As the diver's body converts the oxygen to carbon dioxide via metabolism, and the carbon dioxide is removed by the CO_2 absorbent, the total volume of gas in the breathing loop decreases. Eventually, a diver's full inhalation will cause the counterlung to "bottom-out" (completely collapse), thereby triggering the mechanical valve to add more oxygen. The hazard with this type of system on an oxygen rebreather is that it is vitally important to flush the breathing loop with pure oxygen prior to the commencement of the dive. If a large enough volume of other gasses are in the breathing loop, the diver may suffer from hypoxia (insufficient oxygen) before the counterlung collapses enough to trigger the mechanical oxygen-addition valve. From a design standpoint, oxygen rebreathers are very simple because they do not require a complex *O_2 control system*. However, they are also extremely limited in function because the potential for CNS oxygen toxicity (too much oxygen) prevents safe operation of oxygen rebreathers at depths in excess of about 20 feet/6 meters. In order to safely descend to greater depths, the gas mixture in the breathing loop must contain some constituent other than pure oxygen (e.g., nitrogen or helium). Such mixed-gas rebreathers usually come in one of two forms: semi-closed rebreathers and closed-circuit rebreathers.

Semi-Closed Rebreather

Unlike oxygen rebreathers, semi-closed rebreathers are a form of mixed-gas rebreather, in that they incorporate gas mixtures other than pure oxygen. There are two fundamentally different categories of semi-closed rebreathers: *active-addition*, and *passive-addition*. By far, the most common are the active-addition systems. They are similar in design to the active-addition oxygen rebreathers, except that the supply gas contains a mixture other than pure oxygen. The supply gas is usually injected into the breathing loop at a constant-mass rate. In other words, regardless of the depth, a constant number of molecules of gas are injected into the loop in a given period of time. The rate of injection in such systems must be adjusted according to the fraction of oxygen in the supply gas, such that the rate of oxygen addition to the breathing loop meets or exceeds the rate at which the diver consumes oxygen in the breathing loop.



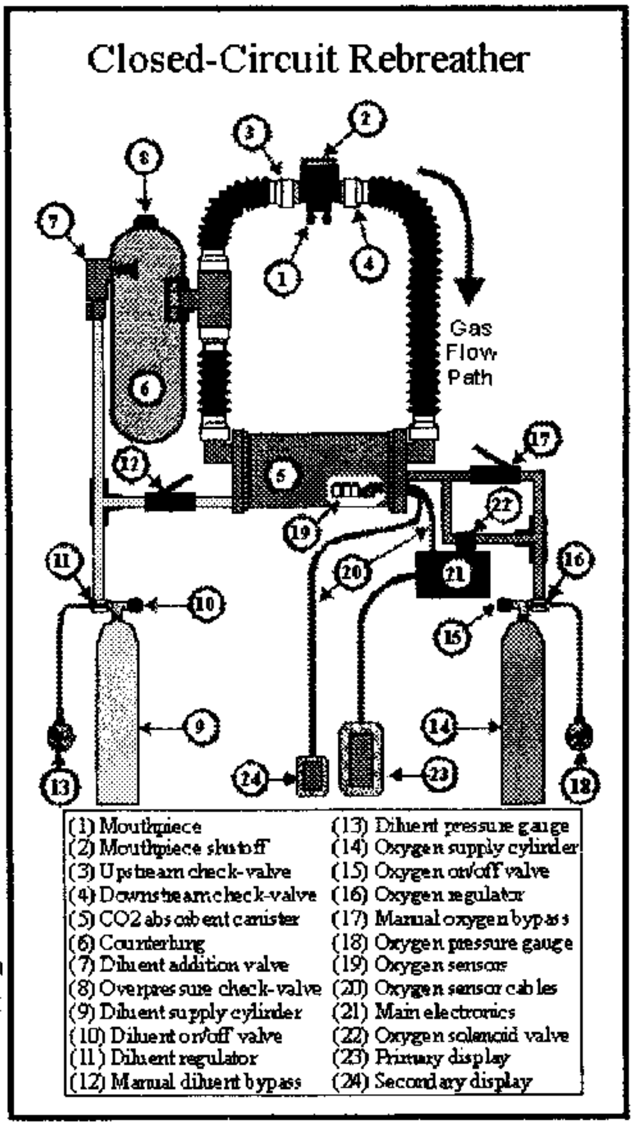
The advantage of this type of rebreather compared with an oxygen rebreather is that it allows divers to descend to greater depths without excessive risk of oxygen toxicity. The disadvantage, however, is the fact that the part of the supply gas that is not oxygen (usually nitrogen or helium, or both) is also added to the breathing loop at a constant rate. Because the diver's body does not consume this "other" gas, it continues to build up in the breathing-loop. To prevent the obvious consequence of over-expansion, this excess gas must be periodically vented out of the breathing loop. In an ideal world, only the non-oxygen component of the breathing gas would be vented from the loop, saving the oxygen for consumption by the diver. However, because the gas in the breathing loop is more-or-less homogeneously mixed, a certain fraction of the vented gas is wasted oxygen.

Another problem with active-addition semi-closed rebreathers is that the concentration of oxygen in the breathing loop is variable. First of all, the oxygen fraction in the breathing loop necessarily "lags" somewhat behind the oxygen fraction in the supply gas. The reason for this is that the diver's body is "pulling" oxygen out of the breathing gas much faster than it is "pulling" out the other constituents of the supply gas. Also, the oxygen is being added to the loop at a constant rate, but the rate at which the diver's body consumes the oxygen varies according to the diver's workload. A given diver's metabolic oxygen consumption rate can vary by a factor of 6 or more in normal conditions, and as much as 10-fold in extreme conditions, depending on the level of exertion. These fluctuations affect the magnitude of the "lag" between the fraction of oxygen in the supply gas, and the fraction of oxygen in the breathing gas. To minimize the risk of hypoxia, the concentration of oxygen in the supply gas and the rate at which the supply gas is injected into the breathing loop must be high enough to accommodate the needs of a diver during heavy exertion. The higher the oxygen fraction in the supply gas, the more restrictive the depth limitation due to the risk of oxygen toxicity during periods of low workload. Furthermore, the greater the gas injection rate, the less time a given volume of supply gas will last (i.e., the less efficiently the supply gas is used). Thus, because of the (usually unpredictable) variability of oxygen needs by the diver during the course of a dive, and the inability of constant-mass flow semi-closed rebreathers to compensate for this variability, active-addition semi-closed rebreathers are inherently inefficient compared to other kinds of rebreathers.

An alternative approach to semi-closed rebreather design is some sort of passive-addition system. Passive-addition designs attempt to adjust the rate at which the supply gas is added to the breathing loop to match more closely the metabolic needs of the diver. The simplest way to make this adjustment in real-time is to "key" the gas injection rate to the diver's breathing rate. In most circumstances, breathing rate, or *respiratory minute volume* (RMV), will be directly proportional to metabolic oxygen consumption rate. Thus, most passive-addition semi-closed rebreathers inject supply gas into the breathing loop at a rate determined by the diver's RMV: more gas is injected during periods of high RMV, and less gas is injected during periods of low RMV. While this approach reduces the problem of large fluctuations in the oxygen content of the breathing gas at different workloads, there is still the need to periodically vent excess gas, thereby reducing gas efficiency.

Closed-Circuit Rebreather

Although the term "closed-circuit rebreather" is often used to refer to any kind of rebreather device, in this context the term will be used specifically in reference to fully closed-circuit, mixed-gas rebreather systems. Like semi-closed rebreathers, closed-circuit rebreathers are a type of mixed-gas system, enabling descent to much greater depths than can be safely reached with oxygen rebreathers. However, there are several important and fundamental differences between semi-closed rebreathers and closed-circuit rebreathers.



The first difference has to do with the way oxygen is added to the breathing loop. Whereas semi-closed rebreathers inject oxygen along with other gases, closed-circuit rebreathers generally consist of at least two independent gas supplies. One of these contains pure oxygen, which is injected into the breathing loop to make up for the oxygen that is consumed by the diver. The other gas supply is called the *diluent*. The diluent usually consists of either compressed air or a special gas mixture such as nitrox (nitrogen-oxygen, usually with higher than normal oxygen concentration than for compressed air), heliox (helium-oxygen, usually with lower than normal oxygen concentration than for compressed air), neox (neon-oxygen) or trimix (usually helium-nitrogen-oxygen). The diluent gas mixture usually contains enough oxygen such that it can be breathed directly from the cylinder via an open-circuit system at the operating depth of the dive. This supply is used to maintain system volume during excursions to depths where the volume of gas in the breathing loop is compressed. In some rebreathers the diluent is also used for the emergency open-circuit bailout gas supply in the event of a total system failure of the rebreather apparatus.

The second major difference between closed-circuit rebreathers and semi-closed rebreathers is how the two systems maintain the concentration of oxygen in the breathing loop. Whereas most semi-closed rebreathers maintain a (more or less) constant *fraction* of oxygen (FO_2) throughout the course of the dive, closed-circuit rebreathers maintain a relatively constant partial pressure of oxygen (PO_2) in the breathing loop. To accomplish this, virtually all closed-circuit rebreathers incorporate some sort of electronic oxygen sensors which monitor the concentration of oxygen in the breathing gas. In most cases, closed-circuit rebreathers also incorporate an electronic O_2

control system, which automatically adds oxygen when the PO_2 drops below a certain level (this level is called the PO_2 set-point).

As discussed below, closed-circuit rebreathers have advantages and disadvantages when compared to open-circuit scuba and semi-closed rebreathers. All of these diving technologies have important applications.

What are the advantages of Rebreathers?

Rebreathers in general, and closed-circuit rebreathers in particular, provide three fundamental advantages over open-circuit scuba systems: more efficient use of gas, optimized decompression characteristics, and near-silent operation.

Gas Efficiency

Perhaps the most significant advantage that closed-circuit rebreathers (and to a lesser extent, semi-closed rebreathers) offer is greatly increased gas efficiency. Under normal circumstances, a diver only uses a small fraction of the oxygen of each inhaled breath; most of the oxygen leaves the lungs unused when the diver exhales. When using open-circuit scuba, the oxygen and other gases in the exhaled gas are wasted in the form of bubbles. As the depth of the dive increases, this inefficiency of open-circuit systems is compounded: because of the increased pressure at greater depths, more gas molecules are lost with each exhaled breath. A rebreather, on the other hand, retains most or all of the exhaled breath, processes it, and returns it to the diver. In the case of closed-circuit rebreathers, because there are almost no exhaled bubbles at all, there is no change in gas usage efficiency at greater depths. Thus, the deeper the dive, the more advantageous (from a gas efficiency perspective) rebreathers become. For example, a standard scuba cylinder contains enough gas to sustain an average resting person for about an hour and a half at the surface. The same cylinder will last only 45 minutes 30 feet / 10 meters underwater, and *less than 10 minutes* at a depth of 300 feet / 90 meters. But if that same cylinder were filled with oxygen and used to supply a closed-circuit rebreather, the diver could theoretically stay underwater for *two days* -- regardless of the depth!

Decompression Efficiency

The second advantage has to do with decompression optimization. This advantage only applies to closed-circuit rebreathers, not oxygen or semi-closed rebreathers. Oxygen rebreathers are limited to depths where decompression is not an issue. The reason it applies only to closed-circuit rebreathers and not semi-closed rebreathers has to do with differences in the breathing gas dynamics of these two types of rebreathers. As mentioned above, semi-closed rebreathers maintain a more-or-less constant *fraction* of oxygen in the breathing gas, whereas closed-circuit rebreathers maintain a constant partial pressure of oxygen in the breathing gas. A closed-circuit rebreather maintains the concentration of oxygen in the breathing gas at it maximum safe value throughout the dive. This means that the non-oxygen portion of the breathing gas (the part that determines decompression obligations), is kept at a *minimum*. This allows the diver to stay longer at depth without incurring a decompression obligation, and also to speed up the decompression process whenever an obligation is incurred.

Silence

With each exhaled breath, a diver using conventional scuba releases a large burst of noisy bubbles.

The effect of this on the behavior of marine-life varies, but in most cases, fishes behave warily and are reluctant to allow a diver to approach closely. Semi-closed rebreathers reduce the volume of exhaled bubbles, and closed-circuit rebreathers essentially eliminate bubbles entirely. With rebreathers, divers are able to approach marine life much more closely while disturbing behavioral patterns much less severely. This is especially important for specimen collection and photographic activities.

What are the disadvantages of Rebreathers?

Discipline and Training

All kinds of rebreathers have certain specific complexities which introduce forms of risk not experienced by scuba divers. The fundamental difference between open-circuit scuba and rebreather systems is that on scuba, if a diver can breathe and is not outside well-established depth limits, the breathing gas is going to be life-sustaining (assuming the cylinder was filled properly). If there is a problem with an open-circuit system, the problem is usually very self-evident to the diver, so the diver at least is aware of the problem and can takes steps toward a solution.

With rebreathers, however, the breathing gas may be dynamic, and thus the oxygen concentration may drift out of life-sustaining range within the course of a single dive. In the case of oxygen rebreathers, if the breathing loop is not adequately flushed prior to commencing the dive, the fraction of nitrogen in the breathing gas may be high. For oxygen rebreathers with passive-addition oxygen control systems, it is possible that the diver may breathe-up all of the oxygen in the breathing loop before the oxygen addition valve is triggered, thus leaving only nitrogen. In the case of semi-closed rebreathers, oxygen concentration in the breathing loop depends on diver workload. Under certain circumstances, especially during high exertion and/or during an ascent, the oxygen concentration in a semi-closed rebreather could drop to dangerously low levels. The inherent weakness of closed-circuit rebreathers is the reliance on electronics to control the oxygen concentration in the breathing loop. As any underwater photographer knows, electronics and water (particularly salt water) do not mix. Indeed, closed-circuit rebreathers have earned a somewhat notorious reputation as being "unreliable", largely due to failures of the electronic O_2 control system (leading to either too much, or too little oxygen in the breathing loop).

These problems can be largely avoided if oxygen rebreathers are adequately flushed with pure oxygen prior to a dive, if the gas supply rate of semi-closed rebreathers is adjusted carefully and the breathing loop is flushed with fresh gas prior to an ascent, and if multiple redundant oxygen sensors and oxygen control systems are incorporated into closed-circuit rebreathers. Unfortunately, symptoms associated with hypoxia and oxygen toxicity cannot be regarded as reliable precursors to black-out. Therefore it is ultimately up to the diver to take steps to ensure a continuous life-sustaining gas mixture in the breathing loop at all times. This level of discipline requires a great deal of discipline and training. Thus rebreather divers must have a higher dedication to equipment maintenance and operation than is generally required for open-circuit divers. Furthermore, rebreathers are generally more complex devices than open-circuit scuba gear, which also accounts for why they require more training time.

Expense

Another disadvantage of rebreathers is monetary expense. Even low-end rebreather designs can cost several thousand dollars, and sophisticated closed-circuit rebreathers can cost as much as $15,000 or more. After the initial purchase price, however, operational expenses are not