REBREATHERS 101

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What's A Rebreather?

A rebreather (RB) is any self-contained breathing apparatus that recycles a diver's breathing mixture. Recycling requires a closed loop for breathing source and exhaust gas. Additionally, to recirculate breathing gases, a scrubbing agent is needed to remove carbon dioxide from the loop. And a bag, or counterlung, is needed to capture diver exhaust respirants. The combination of source mixture, hoses and mouthpiecs, counterlung, and scrubber is called a *breathing loop.* Operationally, RBs vary widely in design and efficiency, but they are generally broken into two categories, *closed circuit rebreathers* (CCRs) and $semi-closed\ circuit\ rebreathers$ (SCRs). Furthermore, CCRs can employ both pure oxygen, or another mixed gas (diluent) plus oxygen. SCRs usually employ just a mixed gas diluent.

What Are The Concerns of RB Divers?

Divers on RBs need concern themselves with both oxygen toxicity and possible decompression constraints. On pure oxygen, oxtox is the only concern, but with mixed gas diluents, decompression may be required. Of course, the higher the oxygen partial pressure, pp_{O_2}, the shorter the decompression requirements on mixed gas diluents. But the higher the oxyygen partial pressure, the greater the risk of oxygen toxicity. Most RB divers maintain pp_{O_2} near the 1.4 atm level, which has an oxygen time limit in the 140 min range (discussed at length in Chapter 5).

Crucial to the operation of RBs is a constant and continuous mass flow of breathing gas, subject to oxygen metabolic requirements and depth. Mass balance simply requires that the flow into the breathing bag equals the amount used by the body plus that exhaled into the breathing bag or exhalation bag. Denoting the breathing gas flow rate, F, the metabolic oxygen (consumption) rate, m, the source oxygen fraction, f_{O_2}, and inspired (breathing bag) oxygen fraction, i_{O_2}, mass balance is written,

$$f_{O_2}F = i_{O_2}F + (1 - i_{O_2})m$$

The source flow rate, F, and oxygen fraction, f_{O_2}, depend on nozzle and mixture. The metabolic rate, m, depends on workload, and the inspired fraction, i_{O_2}, is uniquely determined with the other three specified. Or, for requisite inspired fraction, i_{O_2}, and metabolic rate, m, the source rate, F, and oxygen source fraction, f_{O_2}, can be fixed within limits. Workload rates, m, range, 0.5 - 20.5 l/min, while source flows, F, depend on depth, cylinder and nozzle, with typical values, 5 - 16 l/min. As seen, the source oxygen fraction, f_{O_2}, is uniquely determined by the maximum depth, d_{max}, and maximum oxygen pressure (typically 1.6 - 1.4 atm). Always, inspired oxygen partial pressures are kept between hyperoxic and hypoxic limits, roughly, 0.16 - 1.6 atm. At depth, d, the source flow rate, F, decreases according to,

$$F = \frac{F_0}{1 + d/33}$$

for F_0 the surface rate, unless the flow is depth compensated.

Want Constant Oxygen Partial Pressure Or Constant Oxygen Fraction?

All RBs strive for either constant oxygen partial pressure, pp_{O_2}, or oxygen mix fraction, f_{O_2}, or something in between for dive depth limits, through a combination of injectors, sensors, and valves. High operational oxygen partial pressures coupled to lower inert gas partial pressures minimize decompression requirements, obviously, but oxtox concerns are raised. For fixed oxygen partial pressure, pp_{O_2} in atm, the oxygen fraction, f_{O_2}, depends on depth, d,

$$f_{O_2} = \frac{pp_{O_2}}{1 + d/33}$$

For fixed oxygen fraction, f_{O_2}, oxygen partial pressure varies,

$$pp_{O_2} = f_{O_2}(1 + d/33)$$

In both cases, the total inert gas fraction, f_i, is always given by,

$$f_i = 1 - f_{O_2}$$

and varies little when f_{O_2} is relatively constant.

How Do CCRs And SCRs Differ?

They all deliver constant pp_{O_2} or (roughly) constant f_{O_2}, but there are some major differences impacting the RB diver.

Closed Circuit RBs

Pure oxygen CCRs are relatively simple devices, employing just oxygen in the breathing mixture. Obviously, the are no inert gas decompression requirements on pure oxygen. Oxtox (CNS and full body), however, is a major concern on oxygen CCRs. In such a device, the volume of gas in the breathing loop is maintained constant, and oxygen is added to compensate for metabolic consumption and increasing pressure. On ascent, breathing gas need be vented if not consumed metabolically. Oxygen CCRs inject pure oxygen into the breathing loop, so that, $f_{O_2} = 1$, with corresponding oxygen partial pressure (atm),

$$pp_{O_2} = (1 + d/33)$$

for sea level activities. Because of oxtox concerns, oxygen CCRs are limited for diving, somewhere in the 20 - 30 fsw range in keeping pp_{O_2} below 1.6 atm.

Mixed gas CCRs allow deeper excursions than pure oxygen CCRs by diluting the breathing mix with inert gases, notably nitrogen and helium. Fresh oxygen is injected into the breathing loop only as needed to compensate for metabolic oxygen consumption. Partial pressures of oxygen are measured in the loop with oxygen sensors, and oxygen is injected to maintain constant oxygen partial pressure, called the *set point*. Operationally, mixed gas CCRs are simpler to use than their sisters, mixed gas SCRs. Efficiency and safety concerns obviously track directly to oxygen sensors. Mixed gas CCRs maintain constant oxygen partial pressures, pp_{O_2}, with a combination of diluents and pure oxygen. The oxygen fraction, f_{O_2}, varies with depth,

$$f_{O_2} = \frac{pp_{O_2}}{1 + d/33}$$

and the breathed total inert gas fraction, f_i, makes up the difference,

$$f_i = f_{He} + f_{N_2} = 1 - f_{O_2}$$

for the general case of helium and nitrogen diluents. The oxygen, helium, and nitrogen breathed gas fractions, f_{O_2}, f_{He}, and f_{N_2} vary continuously with depth, d. If the (fixed) diluent helium and nitrogen fraction are denoted, fd_{He} and fd_{N_2}, the breathed helium and nitrogen fractions become,

$$f_{He} = (1 - f_{O_2})\frac{fd_{He}}{(fd_{He} + fd_{N_2})}$$

$$f_{N_2} = (1 - f_{O_2})\frac{fd_{N_2}}{(fd_{He} + fd_{N_2})}$$

Partial pressures at depth for the inert gases are then simply,

$$pp_{N_2} = f_{N_2}(1 + d/33)$$

$$pp_{He} = f_{He}(1 + d/33)$$

and the oxygen partial pressure, pp_{O_2}, is constant.

Semi-Closed Circuit RBs

A semi-closed circuit rebreather (SCR) is very similar to a CCR, but operates with an overpressure relief valve to vent gas in maintaining ambient pressure in the loop. A metering valve is necessary to assess metabolic oxygen consumption and breathing gas injection rates. A number of injection systems exist and all are designed to compensate for metabolic oxygen consumption:

1. Constant Ratio Injection

   SCRs in this category have an oxygen and diluent gas source. Diluent injection varies with depth and oxygen injection links to a mass transport control system. The injection strategy approaches constant pp_{O_2} performance in the breathing loop. In this case, the fraction, f_{O_2}, varies with depth,

   $$f_{O_2} = \frac{pp_{O_2}}{1 + d/33}$$

   and breathed total inert gas fraction, f_i, makes up the difference,

   $$f_i = f_{He} + f_{N_2} = 1 - f_{O_2}$$

   as before for mixed gas CCRs. Retaining diluent fractions, fd_{He} and fd_{N_2}, breathed helium and nitrogen fractions remain,

   $$f_{He} = (1 - f_{O_2})\frac{fd_{He}}{(fd_{He} + fd_{N_2})}$$

   $$f_{N_2} = (1 - f_{O_2})\frac{fd_{N_2}}{(fd_{He} + fd_{N_2})}$$

   Partial pressures at depth for the inert gases are still,

   $$pp_{N_2} = f_{N_2}(1 + d/33)$$

   $$pp_{He} = f_{He}(1 + d/33)$$

2. Constant Mass Flow Injection

   A set gas mixture point controls a constant flow of diluent into the loop. Exhaust is vented through an overpressure relief valve. A single diluent source is employed, while in constant mass flow SCRs, both oxygen partial pressure and oxygen fraction are more variable than in all other RB devices. For depth ranges anticipated, minimal and maximal values of oxygen fraction, f_{O_2}, can be determined from the mass balance equation and used for dive planning contingencies, such as oxtox and decompression, from the above set of equations.

3. Respiratory Volume Injection

   This SCR is a variant of the constant mass flow device. The injection rate of diluent is coupled to the diver's breathing rate, maintaining an almost constant fraction, f_{O_2}, in loop oxygen. Single diluent source is again used. Operationally, a fairly constant f_{O_2} results, and oxygen partial pressure, pp_{O_2}, varies with depth,

   $$pp_{O_2} = f_{O_2}(1 + d/33)$$

and breathed total inert gas fraction, f_i, makes up the difference,

$$f_i = f_{He} + f_{N_2} = 1 - f_{O_2}$$

as above. With same diluent fractions, fd_{He} and fd_{N_2}, breathed helium and nitrogen fractions are roughly constant too,

$$f_{He} = (1 - f_{O_2}) \frac{fd_{He}}{(fd_{He} + fd_{N_2})}$$

$$f_{N_2} = (1 - f_{O_2}) \frac{fd_{N_2}}{(fd_{He} + fd_{N_2})}$$

Breathed inert gas partial pressures vary at depth,

$$pp_{N_2} = f_{N_2}(1 + d/33)$$

$$pp_{He} = f_{He}(1 + d/33)$$

and the oxygen partial pressure, pp_{O_2}, varies as indicated above.

To achieve such ends in flow programmming, RBs are very complex systems. Extensive diver training and technical knowledge are keynoted in RB diving and usage. Are RBs the most efficient means to deep and extended diving short of surface supplied gas and decompression pods?

Guess we would vote yes.