doi:10.3723/ut.29.073 International Journal of the Society for Underwater Technology, Vol 29, No 2, pp 73–78, 2010

A review of the use of closed-circuit rebreathers for scientific diving

Arne Sieber
Poseidon Diving Systems AB, Goeteborg, Sweden, and IMEGO AB, Goeteborg, Sweden
Richard Pyle
Bishop Museum, Honolulu, Hawaii

Abstract

Rebreather diving systems have many advantages to standard open-circuit systems (or SCUBA). Rebreathers offer higher gas efficiency together with silent and bubble-free diving. Moreover, instead of cold and dry gas found in open-circuit systems the diver takes advantage of a warm and humid breathing gas. Stealth (through silent, bubble-free diving) can be beneficial for scientists exploring a range of natural ecological research areas. The high gas efficiency of rebreathers, combined with their lower operational costs, can provide longer autonomy and shortened decompression obligations that may assist the scientist with deeper diving explorations. The present paper gives an overview of today's rebreather technology and focuses especially on the needs of scientific divers. Moreover, it includes a short report about achievements in the field of deep coral explorations, where advanced electronically-controlled closed-loop rebreather systems were the key for efficient and successful missions.

Keywords: closed-circuit rebreathers, eCCR, scientific diving, review, coral reef exploration, trimix

1. Introduction

Decompression obligations, breathing gas consumption, and thermal considerations can place some limitations on how diving is used for scientific gain. Shallow dives (for example, to 40m depth) can be carried out safely using air but as the depth of the dive increases, the available bottom times decreases. Oxygen (O_2) enriched oxygen/nitrogen gas mixtures (commonly referred as NITROX) can be employed as an alternative to air; in the simple two-gas mixture the increase of the O_2 fraction of the mixed gas at the expense of the nitrogen (N_2) fraction reduces the decompression loading and the narcotic potential attributable to N_2 at high partial pressures. The narcotic potential of N_2 means that scientists working beyond 40m often employ Helium (He) enriched gas mixtures (usually as TRIMIX mixtures of $He{:}O_2{:}N_2$). As well as decreasing narcotic potential the other main advantage of TRIMIX is that the partial pressure of O_2 (ppO_2) is kept low reducing the risk of O_2 toxity at depth. Furthermore, the addition of He reduces the overall breathing gas density resulting in a decreased breathing workload. TRIMIX diving usually involves slightly longer decompression stops, which are carried out using separate decompression gas mixtures, and slower ascend speeds in order to avoid micro- and macro-bubble formation. In order to carry sufficient gas supplies to support the descent, the working at depth and the different decompression schedules, TRIMIX divers can often end up diving with a number of cylinders, back- and side-mounted. All that equipment can be very bulky and heavy, and can limit scientific diving activities. Closed-circuit rebreathers represent an alternative life-support system for undersea scientific work through reducing the bulk of an open-circuit TRIMIX system by incorporating the principle of rebreathing of the diver's exhaled gases after CO_2 removal and replacement of the metabolised O_2 with fresh O_2 from a supply tank.

There are a number of specific criteria that are necessary in order to make a rebreather suitable for scientific diving. There is an obvious requirement that any system used is safe with a sufficient level of built-in redundancy. The optimal gas composition should balance the needs of a low narcotic potential with short decompression obligations. A low acoustic signature would enhance the possibility for observing and recording nature with minimal anthropogenic impact. A rebreather intended for use by science divers should be easy to use underwater requiring minimum operational input from the diver during the diving operation in order to maximise the research output. Out of the water, the unit should be easy to maintain and straightforward to train on so that the scientific ''downtime'' is minimised. Finally, a smaller and lighter system will increase the mobility of the scientist underwater.

2. Coral reef exploration

Coral reefs have been reasonably well investigated down to depths of 40–50msw, mostly using conventional SCUBA equipment. Depths below 150m have been researched mostly with submersibles and unmanned vehicles (AUVs, ROVs). In contrast to these two undersea regions, very little is known about the intermediate zone between 50msw and 150msw – variously referred to as the coral-reef ‘‘Twilight Zone’’ and more recently ‘‘Mesophotic Coral Ecosystems’’. This zone has been the focus of a series of exploratory expeditions by the second author, from 1988 through to the present (Pyle, 1991, 1992, 1996a,b, 1998, 2000). From 1988 through 1993, these dives were conducted using open-circuit TRIMIX gear; and from 1994 until the present they were made using mixed-gas electronically-controlled closed-circuit rebreather systems (eCCR; Cis-Lunar Mk4P and Mk5P systems).

3. Efficiency of open circuit diving

A typical open-circuit diving system (SCUBA) for recreational purposes consists of a single gas storage cylinder (typically 7–18L with filling pressures from 200–300bar) and a two-stage pressure regulator (NOAA Diving Manual, 2001; U.S. Navy Diving Manual, 2008). The first stage of the two-stage regulator reduces the tank’s pressure to an intermediate pressure around 8–10bar higher than ambient pressure. Through allowing the water to have direct access to the second stage diaphragm, the regulator reduces the intermediate pressure to ambient pressure, thus allowing the diver to breathe with minimal resistance. Exhaled air is then vented through an exhaust valve into the water. The maximum time a diver can stay under water is determined mainly by the amount of gas being carried, the depth of the dive, and the diver’s breathing rate and volume.

A normal relaxed diver metabolises approximately 0.8–1.0barLmin^{-1} O_2 (Ehm et al., 2003). This O_2 consumption may increase up to 2.5–3.5barLmin^{-1} in the case of hard physical activities. As an example: a diver has a surface breathing minute volume of 25barLmin^{-1}; this volume contains approximately 5.25barLmin^{-1} O_2. However, only 0.8barLmin^{-1}O_2 is metabolised which is equivalent to a gas efficiency of approximately 3% (only 0.8barL of the total 25barL gas supply are being used by the diver). As the pressure increases with depth, this ratio decreases: at 40msw a diver breathing at a surface-equivalent rate of 25Lmin^{-1} will consume 125barLmin^{-1} because of the increased pressure (5bar absolute at 40msw compared with 1bar at sea-level). The O_2 metabolism rate remains at 0.8barLmin^{-1} and so the gas efficiency at 40m drops to approximately 0.6% (0.8 from 125barLmin^{-1}). A cylinder with 10L volume pressurised to 200bar contains an equivalent of 2000L which, when breathing at 125Lmin^{-1} (and assuming no reserves), would last 16min. At a depth of 100msw, the efficiency drops to 0.3% and, largely for this reason, conducting dives to 100msw or more using open-circuit equipment is impractical because an enormous amount of gas supply needed. Those needs at greater depths are then multiplied by long decompression obligations that may last several hours.

Large volumes of gas carried in a SCUBA rig obviously become very bulky and limit the diver’s ability to move freely, hampering many kinds of research activities. However, large gas consumption also carries a cost issue, especially when it comes to expensive He-enriched gas mixtures. Open-circuit diving also carries additional drawbacks such as cold caused by adiabatic cooling during gas expansion and the prolonged breathing of dry gases. Even though the diver may be limited to a small number of breathing mixtures (optimised for decompression purposes for use only at specific depths) each tank may weigh *circa* 20kg and the diver may be carrying six to eight tanks. Such a diving rig can be very bulky and limits the diver’s ability to move freely, hampering some kinds of research activities.

4. Rebreathers

The efficiency of gas breathing can be increased by using a rebreather (Mount and Gilliam, 1992; Shreeves and Richardson, 2006). When using open-circuit SCUBA the exhaled gas is vented into the surrounding water, where it is wasted. In a rebreather, the exhaust breath is recirculated through a loop (e.g. Figure 1, which shows the schematics of a simple oxygen rebreather), into a flexible bag (the so-called counterlung). A chemical absorbent material removes carbon dioxide followed by the addition of fresh gas to substitute for the metabolised O_2 content. The recycled gas is then inhaled by the diver again.

All rebreathers, irrespective of the gas mixtures being used, carry a risk of oxygen toxicity which is a factor of the oxygen content of the mixture and the depth at which it is being breathed. The partial pressure of O_2 (ppO_2) inside the loop is dependent on the ambient pressure (equivalent to depth); pressure increases through a linear relationship of 1bar pressure for every 10msw (plus the surface pressure of 1bar exerted by the atmosphere), with the partial pressure relationship adhering to Dalton’s Law of Partial Pressures. The present recommended ppO_2 limits for diving

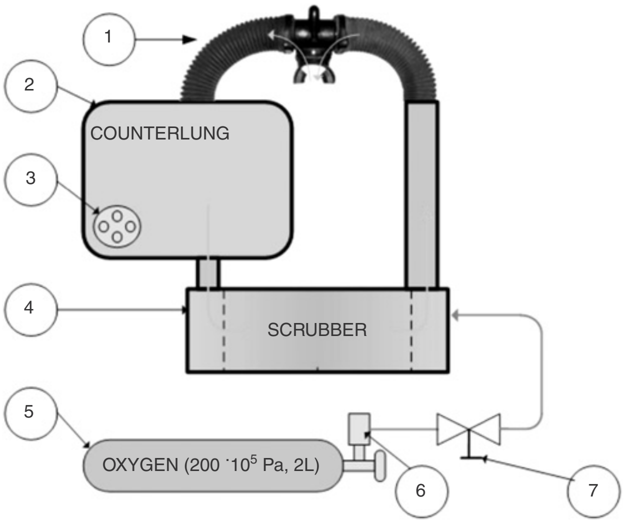

Fig 1: Schematics of an O_2 rebreather (1: mouthpiece, 2: counterlung, 3: overpressure valve, 4: scrubber, 5: oxygen tank, 6: first stage pressure regulator, 7: manual valve)

breathing gases range from 0.14bar (14.1kPa) to 1.6bar (162kPa). Breathing gas mixtures containing ppO_2 levels above the upper limit increases the potential for acute oxygen toxicity, manifested as an epileptiform convulsion, which underwater is likely to be fatal as the diver could lose his mouthpiece, inhale water and drown; breathing gases with ppO_2 values below 0.14bar (14.1kPa) risks unconsciousness.

Using a ppO_2 limit of 1.6bar limits the depth for pure O_2 rebreathers to 6msw, and pure O_2 rebreathers are usually used only for military applications. Deeper rebreather diving requires a diluent gas in the loop to maintain a constant (but sometimes variable) ppO_2 value even as pressure increases.

Rebreathers are classified as either semi-closed circuit rebreathers (SCRs) or manually or electronically controlled closed-circuit rebreathers (mCCR or eCCR, respectively). The constant mass flow SCR is the simplest form of a SCR. In such a system O_2-enriched air enters the breathing loop via a constant flow injector (typically at 6–12barLmin^{-1} depending on the oxygen content of the gas which, in turn, is influenced by the safe maximum operating depth for that mixture) from a relatively small tank to substitute the metabolised O_2. As the volume of the breathing loop gradually increases, a corresponding amount of excessive gas is then vented through an overpressure valve. SCRs are easy to use, easy to maintain and usually do not need electronics for a safe operation. Even though a certain amount of gas is vented, the acoustic signature is already dramatically reduced in comparison to open-circuit, especially when a so called ''bubble diffuser'' is installed. This particular advantage, which allows closer interaction with life-forms, made the SCR units popular with underwater photographers, cameramen and also researchers (e.g. Sayer and Poonian, 2007).

In a mCCR or an eCCR the ppO_2 is usually kept at constant level with only the metabolised O_2 being replaced from a separate source of 100% O_2 (Figure 2). The breathing gas in a closed rebreather contains also N_2 and/or He in the form of ''diluent gas'' in order to maintain a safe ppO_2 limit while avoiding any narcotic effects of high ppN_2 levels. The diluent gas can be supplied either in the forms of air or TRIMIX from a separate tank (Figure 2). To keep the ppO_2 at a constant level, a control system is needed and electrochemical oxygen sensors, whose output signal is proportional to the partial pressure of O_2, provide a feedback mechanism (Baran, 2004). In a mCCR, the diver reads the ppO_2 from a display and, if needed, adds O_2 manually. In an eCCR, this regulation task is usually performed with a combination of microcontroller solenoid valves (Straw, 2005).

As outlined above, open-circuit SCUBA diving has low gas utilisation efficiency, varying from less than 5% on the surface, to below 0.5% at 100msw. With CCRs, because the breathing gas is recycled and, under optimal conditions, only the metabolised O_2 is replaced, gas efficiency may approach 100%. This high efficiency rate permits the design of comparatively small, lightweight systems where gas costs and supply are no longer significant limiting factors. In addition, because of the recirculation with minimal wastage, CCRs allow bubble-free, silent diving. Only during the ascent is gas vented from the circuit caused by the gas volume in the loop increasing inversely in proportion to the decreasing pressure. Another advantage of using rebreathers is that the breathing gas is usually warm and humid, caused by the chemical process of CO_2 absorption in the scrubber canister, producing water and heat as by-products. Finally, because the CCR maintains a constant ppO_2, the breathing mixture is optimised for decompression purposes at all points during the dive.

5. Limitations of closed circuit rebreathers

One of the main problems of rebreathers in comparison with SCUBA is the increased complexity of the breathing system. While a failure in open-circuit is usually quite easy for most divers to detect and correct, problems with CCRs may often be hidden and may have an increased potential to cause harm or be fatal (Vann et al., 2007, Central Database of Rebreather Fatalities). The most commonly identified systems failures which have the potential

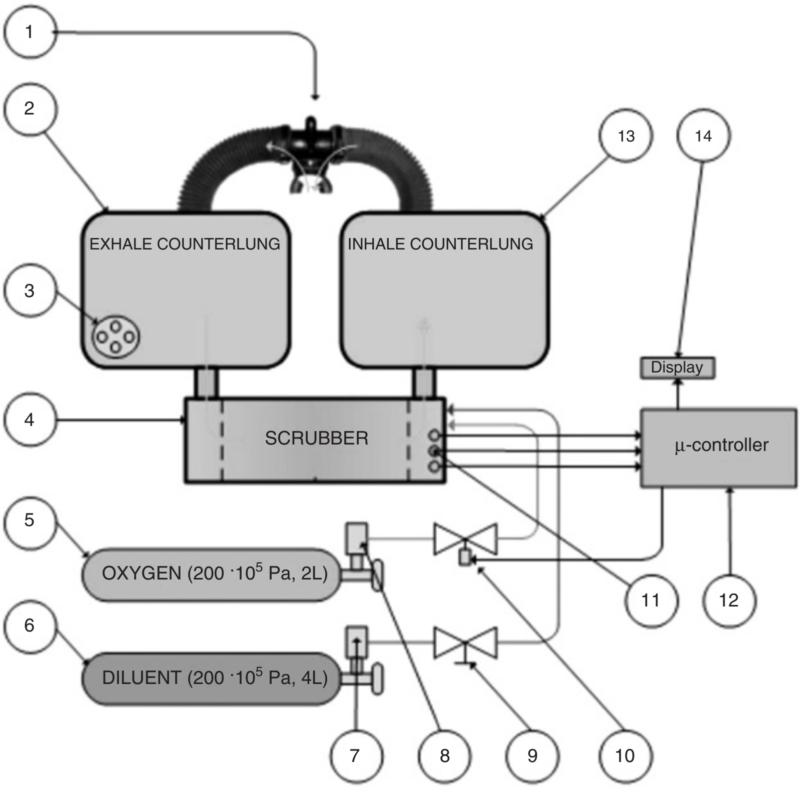

Fig 2: Schematics of an electronic closed-circuit rebreather (eCCR; 1: mouthpiece, 2: exhale counterlung, 3: overpressure valve, 4: scrubber, 5: oxygen tank, 6: diluent tank, 7, 8: pressure regulators, 9: manual diluent vlave, 10: solenoid, 11: pO_2 sensors, 12: μ-processor, 13: inhale counterlung, 14: display)

to be life threatening are a loss of maintenance of ppO_2 levels outside of life-sustaining limits, increased CO_2 levels and water leakage into the breathing circuit.

High CO_2 levels can be avoided through efficient scrubber design combined with conservative scrubber management. Latest developments use pre-packed scrubbers to avoid poor scrubber filling methods which may cause channelling which can raise CO_2 levels through ineffective contact. Scrubber efficiency may also be impaired in cold temperatures and should be well-researched before use in extreme environments.

Water ingress to the breathing circuit can result in a reaction with the scrubber chemicals to cause the so called 'caustic cocktail'. Some CCRs address this issue by incorporating hydrophobic membranes at the inlet and/or the outlet of the scrubber in order to prevent water from entering or leaving the scrubber.

A malfunction of the control system, irrespective of whether it is manual or automatic control, may easily result in dangerously high or low ppO_2 values inside the breathing loop. Solenoid valves (that replace the metabolised oxygen in automatic control systems) and manually actuated mechanical gas injection devices, like orifices or gas bypasses, can be designed very robustly and are usually reliable. Failures can be detected easily and, in the case of a good system design, the problem can be resolved. The state of the art for the electronic components is to use redundant designs and/or networks of microcontrollers where incorrect function of one node can be detected by the others which, in turn, can trigger an alarm. The weakest elements in any ppO_2 control system within a rebreather are the ppO_2 sensors.

6. ppO_2 measurement

Current rebreathers use electrochemical ppO_2 sensors, each one consisting of two electrodes of dissimilar metals. The cathode is made from a noble metal behind a diffusion barrier (usually Teflon); the anode is usually made from lead. The electrodes are held in contact with a liquid or semisolid basic electrolyte, usually potassium hydroxide; when the sensor is exposed to the breathing gas, O_2 diffuses through the teflon membrane and is chemically reduced at the surface of the cathode to hydroxyl ions. The hydroxyl ions then flow toward the lead anode, where an oxidation reaction occurs generating an electrical current proportional to the ppO_2. In most cases, a resistor is incorporated in the electrical circuit, thus the output from the sensor is measured in mV. Many sensors incorporate temperature compensation in the electronics.

Typical specifications for an O_2 sensor for diving purposes are measurement ranges of 0–100% and 0–2bar O_2, a signal output of 8–13mV at 0.21bar O_2 with a linear slope of 40–65mV per bar O_2 pressure, and a 90% response time of 6s. In the reaction with O_2, the anode is partially consumed which is the limiting factor determining the lifetime of the sensor, typically 12–24 months.

O_2 sensors typically fail because of non-linear responses to O_2 concentrations, current limitation (the output signal of the sensor is limited thus will remain constant above a certain ppO_2), a slow signal response and mechanical or electrical damage. The most common failure mode is not achieving the correct electrical output for a given ppO_2 resulting in a rapid delivery of a breathing gas with a composition outwith life-sustaining limits. Non-linearity and current limitation may deliver potentially dangerous elevations of ppO_2 if measurement is in error below the maximum safe operating limits.

Until recently, ppO_2 was normally measured in commercially-available rebreathers through the use of three oxygen sensors with some form of voting logic to determine the correct ppO_2: the three sensor signals were continuously compared with each other; if one sensor output was deviating from the other two it was voted as faulty and not used for further ppO_2 control. Such a design, normally referred to as a ''voting algorithm'', implicitly assumes that sensor failures are independent and that no two sensors would fail at the same time from the same cause. A new approach is based on automatic and true validations of the performance of an O_2 sensor throughout the dive (Sieber et al., 2008; Shreeves, 2009). This is done by periodically exposing the primary sensor to a known ppO_2 and determining that the sensor responds correctly. This is achieved by injection of diluent gas and O_2 directly in front of the sensor membrane which permits determination of correct sensor behaviour as well as ensuring a linear response into the hyperoxic region. Use of a second (truly redundant) pO_2 sensor allows detection of other classes of failures, including leaking solenoids.

In order to work efficiently underwater, the scientific diver must be able to concentrate on the main project objectives but often within the context of limited bottom times and/or where additional bottom time generates unrealistic decompression obligations. eCCRs generally work autonomously although require attention and intervention from the user like, for example, continuously monitoring the ppO_2 sensors and validating the control system by flushing the loop with diluent manually. However, these tasks interrupt work flow and, as a consequence, can reduce efficiency of the scientific diver. Automation of these tasks with microcontrollers may be a solution to reduce workload, increase operation safety, improve efficiency (including a reduced training requirement) and reduce pre- and post-dive preparation/maintenance of the unit.

7. Conclusions

In the years between 1994 and the present, several expeditions employed deep-diving techniques to explore deep coral reefs. During that time, more than a hundred new species of fishes have been discovered (Pyle et al., 2008). The rate of discovery increased from about seven new species of fishes discovered per hour of exploration time with open-circuit TRIMIX gear, to more than eleven per hour when using rebreathers (Pyle et al., 2008). Comparisons between open-circuit TRIMIX and mixed-gas CCR, showed the CCR to generate seven times more productive bottom time relative to support time (Parrish and Pyle, 2001, 2002). Besides increased efficiency, the CCRs had lower operational costs (in the case of TRIMIX diving) because of the reduction in wastage. Studies have shown that divers observe much higher numbers of fish while using rebreathers compared with using open-circuit (Sayer and Poonian, 2007).

Many studies have demonstrated the potential of rebreathers to maximise the working efficiency of scientific divers. However, rebreathers are used in scientific diving rarely, mainly because of the complexity of the systems, the required high level of training and the time taken with pre- and post-unit maintenance. Full automation has the potential to optimise the diving time while reducing distractions such as continuous system monitoring or improving the ease of routine monitoring through the employment of head up displays (HUDs) that, in case of a failure, prompt the diver to switch to open circuit or an alternative redundant breathing loop. Unfortunately today there is no automatic and completely redundant rebreather on the market that supports deep explorations. The introduction of an automated system with full TRIMIX capability and redundant operation modes (manual control and semi closed modes) will present a host of new opportunites for the diving scientist.

References

Baran U. (2004). *WO/2004/112905: Diving Equipment Monitor.* http://www.wipo.int/pctdb/en/wo.jsp?WO=2004112905, [last accessed: 07 June 2010].

Central Database of Rebreather Fatalities. http://www.deeplife.co.uk/or_accident.php, [last accessed: 07 June 2010].

Ehm OF, Hoffmann U and Wenzel J. (2003). *Der neue EHM Tauchen noch sicherer*. Cham (CH): Müller Rüschlikon Verlag, 552pp.

NOAA Diving Manual. (2001). *Diving for Science and Technology*, 4th edition. Springfield, USA: US Department of Commerce, National Technical Information Service, 660pp.

Mount T and Gilliam B (eds.). (1992). *Mixed Gas Diving: The Ultimate Challenge for Technical Diving*. San Diego: Watersport Publishing, Inc, 392pp.

Parrish FA and Pyle RL. (2001). Surface logistics and consumables for open-circuit and closed-circuit deep mixed-gas diving operations. In: Proceedings of the Marine Technology Society and the Oceanic Engineering Society of the Institute of Electrical and Electronic Engineers Oceans 2001 Conference **3**: 1735–1737.

Parrish FA and Pyle RL. (2002). Field comparison of open-circuit scuba to closed-circuit rebreathers for deep mixed-gas diving operations. *Marine Technology Society Journal* **36**: 13–22.

Pyle RL. (1991). Rare and unusual marines: so many fish, so little time. *Freshwater and Marine Aquarium* **14**: 42–44.

Pyle RL. (1992). The twilight zone. *Aquacorps* **3**: 19.

Pyle RL. (1996a). How much coral reef biodiversity are we missing? *Global Biodiversity* **6**: 3–7.

Pyle RL. (1996b). The twilight zone. *Natural History Magazine* **105**: 59–62.

Pyle RL. (1998). Use of advanced mixed-gas diving technology to explore the coral reef ''Twilight Zone''. In: Tanacredi JT, Loret J. (eds.). *Ocean Pulse: A Critical Diagnosis*. New York: Plenum Press, 71–88.

Pyle RL. (2000). Assessing undiscovered fish biodiversity on deep coral reefs using advanced self-contained diving technology. *Marine Technology Society Journal* **34**: 82–91.

Pyle RL, Earle JL and Greene BD. (2008). Five new species of the damselfish genus *Chromis* (Perciformes: Labroidei: Pomacentridae) from deep coral reefs in the tropical western Pacific. *Zootaxa* **1671**: 3–31.

Sayer MDJ and Poonian C. (2007). The influences of census technique on estimating indices of macrofaunal population density in the temperate rocky subtidal zone. *Underwater Technology* **27**: 119–139.

Shreeves K. (2009). Winner: Poseidon Discovery. *Institute of Electrical and Electronics Engineers, Spectrum* **1.2009**, 20–21. [http://spectrum.ieee.org/geek-life/tools-toys/winner-poseidon-discovery; last accessed: 29 June 2010].

Shreeves K and Richardson D. (2006). Mixed-gas closed-circuit rebreathers: an overview of use in sport diving and application to deep scientific diving. In: Lang MA, Smith NE. (eds.). Proceedings of the Advanced Scientific Diving Workshop. Washington, DC: Smithsonian Institution, 135–151.

Sieber A, L'Abbate A and Bedini R. (2008). Oxygen sensor signal validation for the safety of the rebreather diver. *Diving and Hyperbaric Medicine* **39**: 38–45.

Straw PE. (2005). *WO/2005/107390: Rebreather setpoint controller and display*. http://www.wipo.int/pctdb/en/wo.jsp?wo=2005107390, [last accessed: 07 June 2010].

U.S. Navy Diving Manual, Revision 6. (2008). SS521-AG-PRO-010. Direction of Commander, Naval Sea Systems Command, USA. 992pp. http://www.scribd.com/doc/8162578/US-Navy-Diving-Manual-Revision-6-PDF, [last accessed: 07 June 2010].

Vann RD, Pollock NW and Denoble PJ. (2007). Rebreather fatality investigation. In: Pollock NW, Godfrey JM. (eds.). *Diving for Science 2007*. Dauphin Isl., AL: American Academy for Underwater Sciences, 101–110.