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Breathing Like a Fish

By Petros J. Katsioloudis

Being able to dive and breathe underwater has been a challenge for thousands of years.

Homer, in his *Iliad* (750 B.C.), refers to charioteers falling from their chariots like divers. The great Aristotle refers, in his *Problemata* (360 B.C.), to what might have been a diving bell, and of course the genius Leonardo da Vinci (1500), in his notebook, showed various types of diving appliances (Quick, 1970). Being able to dive and breathe underwater has been a challenge for thousands of years. Jacques Cousteau was quoted as saying "It will happen my friends, surgery will affix a set of artificial gills to man's circulatory system—right here at the neck—that will permit him to breathe oxygen from the water like a fish. Then the lungs will be bypassed, and he will be able to live and breathe in any depth for any amount of time without harm. It will happen, I promise you." (ScubaSuperPower, 2007). Of course, most of us would prefer not to have to resort to surgery; therefore, the question remains: Could new technological developments allow us to create a practical artificial gill?

According to Page (2006), making a crude artificial gill is surprisingly easy. All you need is a watertight box made out of a membrane that is highly permeable to gas. Fill it with air and put it underwater, and you've got a gill (Page, 2006). During the filtration process, the levels of oxygen and CO_2 dissolved in water are in equilibrium with the atmosphere above them, so diffusion through the membrane will result in concentrations close to those of the atmosphere inside the box. If the oxygen level in the box falls, more oxygen will diffuse in from the water, and any excess CO_2 will diffuse out.

In 1980, Fuji Systems of Tokyo developed a series of prototype gills for divers as a way of demonstrating just how good its membranes are. The early versions resembled a small fridge strapped to a diver's back, while the most advanced prototype, called the Donkey III, consists of a coffin-shaped box that has to be pushed in front of the diver. It's huge, but it does work. In a televised demonstration in 2002, it supported a diver in a swimming pool for 30 minutes (Page, 2006). Even though gill technology has not yet reached the point where recipients can efficiently use implants to dive underwater, mechanical devices such as "rebreathers" are able to mimic the biological process.

Rebreather

A rebreather is an electromechanical device that can provide breathing gas through infusion of oxygen and recycling of carbon dioxide through the use of a chemical scrubber (Figures 1 and 2). Since the diver doesn't release any air, the recycling process reduces the volume of breathing gas necessary, making a rebreather a lightweight and compact breathing set for long durations in environments where humans cannot safely breathe from the atmosphere. Most types of today's rebreathers consist of a breathing loop, a canister where the scrubber can be stored along with the pO_2 sensors, the breathing lungs, and some type of interface devices such as handheld computers and a HUD (Heads-up Display) to show pO_2 levels.

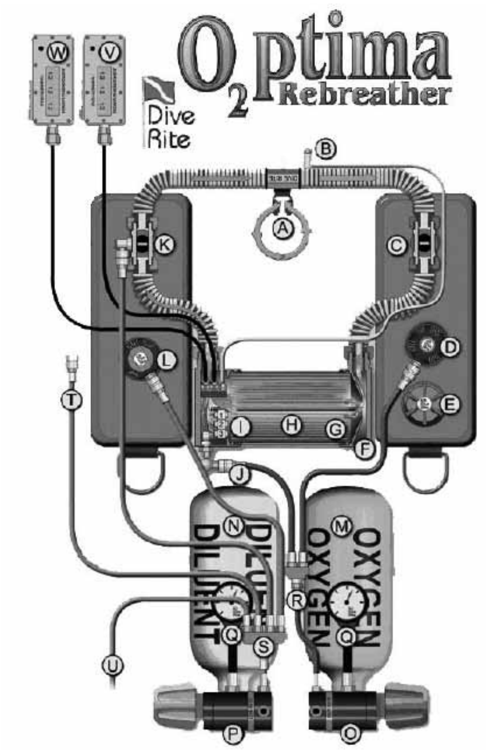


Figure 1. Shown here is a conceptual diagram of a closed circuit (CCR) rebreather system. Typically rebreather systems use an electronically controlled mixing valve that blends a breathable gas from two separate cylinders. The cylinder on the left, the diluent, is normally used to make up the volume of the breathing loop while the cylinder on the right is used to achieve the desired gas blend. The second cylinder is usually 100% oxygen. (Courtesy of DiveRite)

Figure 2. A semiclosed rebreather system recirculates the exhaled gases from the diver into a counter-lung or breathing bag. The exhaled gas contains less oxygen and an increased amount of carbon dioxide. The exhaled gas needs to pass through a chamber to remove the CO_2 before being consumed again. This chamber is called a "scrubber" and generally is made up of a manufactured cartridge. The scrubbing process removes the excess CO_2. (Courtesy of DiveRite)

History

The first known closed-circuit breathing device using stored oxygen and absorption of carbon dioxide by an absorbent (caustic soda) was invented by Henry Fluess in 1879 to rescue mine workers who were trapped by water (Davis, 1955). Fleuss' first apparatus was a watertight, stiffened rubber mask fitted over the face, and into it ran two breathing tubes from a flexible bag worn on the diver's back. The bag was connected to a copper tank of oxygen compressed to 30 atmospheres. The exhalations returned through the bag, where an absorbent removed the carbon dioxide product of breathing. The absorbent was comprised of rope yarn soaked with a solution of caustic potash (Quick, 1970).

According to Quick (1970), the Davis Escape Set was the first practical rebreather system produced in quantity. It was designed about 1900 in Britain for escape from sunken submarines. Various industrial oxygen rebreathers (e.g., the Siebe Gorman Salvus and Siebe Gorman Proto) were descended from it. The Proto (distinguish from "Proton") was much used by firefighters (Quick, 1970).

Rebreather Concerns

One of the concerns that divers need to be aware of during the use of any kind of rebreather is keeping the pO_2 (Partial Pressure) within the acceptable limits. On the surface, the amount of oxygen contained within the atmospheric air is 21% under 1 atmosphere of pressure (atm). During a dive, the atmospheric pressure increases by 1 atmosphere at every 33 feet, which means that if a diver is at a depth of between 1 and 33 feet, the amount of oxygen infused in the body will be doubled, since we now have 1 atmosphere in the water and 1 in the surface that equal 2 x .21= .42. Breathing any mixture at depth with a pO_2 of .4 or lower is considered hypoxic due to inadequate oxygen supply that, in most cases, can be fatal for the diver. On the other hand, if the diver breathes gas mixtures where pO_2 exceeds 1.4, the environment is considerd hyperoxic. Hyperoxia can lead to oxygen toxicity, which in most cases is also fatal for the diver. Most divers prefer to maintain a pO_2 of 1.2 that allows sufficient dive time and is within the safety limits. In a case of an oxygen rebreather, since the air used is pure oxygen, it cannot be used in any depth below 20 feet where it becomes toxic. Another concern, of equal importance as the pO_2 limits, is hypercapnia. Since all rebreathers use some kind of an artificial CO_2 absorbent (commonly known as a scrubber), there is always the possibility of failure of the scrubber. In that condition, an excess amount of CO_2 (known as hypercapnia) will be present in the breathing loop that can put the diver to sleep and eventually cause drowning. At this point in time, there is no technology trustworthy enough to monitor the efficiency status of the scrubber; therefore, most divers operate conservatively and are aware not to exceed the manufacturer's suggested time of use.

Different Types of Rebreathers

Oxygen Rebreather: The oxygen rebreather is the oldest type of rebreather. Mainly used by the navy, the only gas that it supplies is oxygen. Through the breathing tube, the used gas will travel into the scrubber where a percentage of the carbon dioxide created through the breathing process will be recycled due to a chemical reaction that subtracts CO_2 and releases oxygen. The same amount of gas enriched with oxygen will then be sent back to the diver to breathe. Since pure oxygen is toxic when inhaled at pressure deeper than 20 feet, this kind of rebreather had too many limitations. Oxygen rebreathers are no longer commonly used in diving because of the depth limit imposed by oxygen toxicity.

Semi-Closed-Circuit Rebreather. The semi-closed rebreather is one of the most commonly used by recreational divers. This type of rebreather provides better underwater duration than open circuit types, allows a deeper maximum operating depth than oxygen rebreathers, and is easier to operate and maintain. Also, the cost of the semi-closed unit is less relevant than the other kinds.

A semi-closed-circuit rebreather generally supplies one breathing gas, such as air or Nitrox or Trimix. The advantage of using a gas different than pure oxygen is that it allows the diver to dive deeper than the 20-foot limitation of the oxygen rebreather. The gas is injected into the loop at a constant rate to replenish oxygen consumed from the loop by the diver. Excess gas must be constantly vented from the loop in small volumes to make space for fresh, oxygen-rich gas. Since the oxygen in the vented gas cannot be separated from the inert gas, a semi-closed-circuit system is wasteful of oxygen, which results in limited dive time. As the amount of oxygen required by the diver increases with work rate, the gas injection rate must be carefully chosen and controlled to prevent unconsciousness in the diver due to hypoxia (Elliot, 1997).

Fully Electronic Closed-Circuit Rebreather. Closed-circuit rebreathers generally supply two breathing gases to the loop: pure oxygen and diluent or diluting gas such as air or trimix. Having a dual mix of gases, with none of them being supplied at a constant rate, allows the diver to control the oxygen concentration, known as partial pressure in the loop, and to increase dive time.

In fully electronic closed-circuit systems such as the Optima Fx made by Dive Rite, a mechanism (known as the solenoid) injects oxygen into the loop when it detects that the pO_2 in the loop has fallen below the required level. Often this mechanism is electrical and relies on oxygen-sensitive electro-galvanic fuel cells, known as "ppO_2 sensors," to measure the concentration of oxygen in the loop.

The diver may be able to manually control the mixture by adding diluent gas or oxygen. Manual addition of gas allows the diver to control buoyancy, especially during ascent, where pO_2 drops and the unit is trying to maintain the preset oxygen levels by adding oxygen in the loop.

Credit: Author.

Figure 3. The fully electronic closed-circuit rebreather employs an electronic-controlled gas mixing system that blends the gas from two separate cylinders and gives the diver the best mixture at any depth.

Career Connections

Many people associate underwater diving with Navy Seals and frogmen in the military service. However, a closer examination of diving as a career has many specialties that include recreational and professional areas such as free diving, snorkeling, SCUBA (Self-Contained Underwater Breathing Apparatus), surface-supplied diving, and rebreather systems that are used in recreation, construction, and maintenance, as well as exploration and research career paths. Generally, diving careers do not require college degrees, but require specialized training by certified instructors as well as work experience. Commercial divers may receive training through an apprenticeship, private training organization, or training in the military service. However, research and exploration divers may require degrees in oceanography, biology, physics, and other related disciplines in addition to specialized diver training. Typically, research and exploration divers are employed by universities and research institutions.

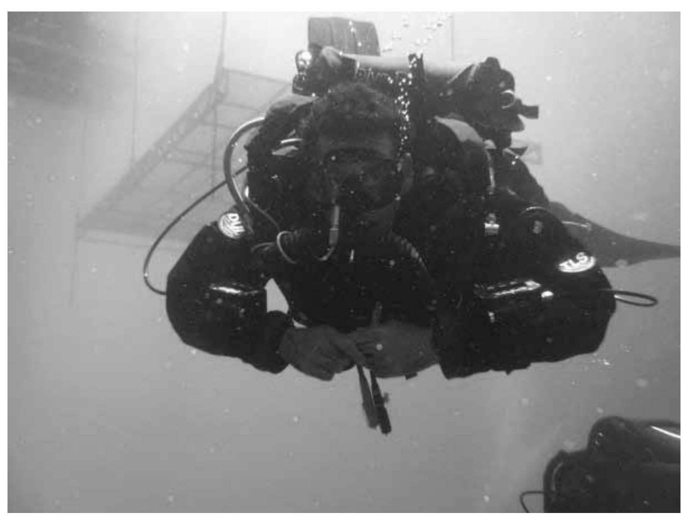
Professional commercial divers may use SCUBA or surface breathing equipment to inspect, install, or remove structures and equipment located underwater. Divers may expect to use tools such as hammers, drills, saws, wrenches, and other tools underwater to fabricate and repair structures. Salaries for professional and commercial divers may range from $40,000 to $100,000 per year. Good health and physical condition is necessary for careers in diving. The following skills and competencies are reflective of the responsibilities of commercial divers (OneNet Online):

- Communicate with workers on the surface while underwater, using signal lines or telephones.
- Take appropriate safety precautions, such as monitoring dive lengths and depths, and registering with authorities before diving expeditions begin.
- Check and maintain diving equipment such as helmets, masks, air tanks, harnesses, and gauges.
- Descend into water with the aid of diver helpers, using scuba gear or diving suits.
- Obtain information about diving tasks and environmental conditions.
- Inspect and test docks, ships, buoyage systems, plant intakes and outflows, and underwater pipelines, cables, and sewers, using closed-circuit television, still photography, and testing equipment.
- Repair ships, bridge foundations, and other structures below the water line, using caulk, bolts, and hand tools.
- Cut and weld steel, using underwater welding equipment, jigs, and supports.
- Recover objects by placing rigging around sunken objects, hooking rigging to crane lines, and operating winches, derricks, or cranes to raise objects.
- Install pilings or footings for piers and bridges.

Design Initiative for Students

One of the most important components of the rebreather is the one-way valve located at each end of the tube to insure directional gas flow through the loop. The normal flow is clockwise, with the inhalation coming from the diver's left side and exhaling to the diver's right side so used gas doesn't mix with new. To best demonstrate how a one-way valve works, you can have your students build one. The materials necessary for this activity are: two 8-inch sections of clear plastic tubing, 1-2 inches in diameter, a small elastic band, scissors, a rubber glove (such as those used for dishwashing), duct tape, a cup, and water. First use scissors to cut off one of the fingers from the glove. Then cut an "X" in the tip, with each slit about one-inch in length. Insert the glove finger into one section of wide, clear plastic tubing and invert and roll a small section of the fabric of the glove back over the tube to form a collar.

Secure the exposed collar to the plastic tube with either duct tape or an elastic band and place the other tube section on top of the balloon end of this tube. Use duct tape to secure and form a waterproof seal around the joined edges of the two tubes. Fill a small cup with water over a sink and carefully pour the water into the tube assembly so that it flows into the inside of the glove finger. Observe what happens as the fluid impacts the glove finger, and then turn the tube assembly upside down and again



Credit: Author.

Figure 4. Even though the use of the rebreather offers multiple advantages, special training is required for safe use.

pour a cup of water into the tube. What happens this time? Write down your observations.

Activities such as the one described above are easy to correlate with the technological literacy standards created by the International Technology Education Association in 2000. See Table 1 for correlations with the *STL* standards.

Summary

As we look at the new inventions and innovations in the technology of underwater equipment, we can see that through the years they are becoming more technologically advanced. We see examples such as the Optima Fx rebreather, where an electronic-controlled gas mixing system blends the gas from two separate cylinders and gives the diver the best mixture at any depth. However, the main goal of these devices—to allow the presence of humans in impossible-to-visit areas, such as underwater caves and blue holes—remains the same, and their importance to exploration will remain vital.

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Table 1. Correlation with *Standards for Technological Literacy (STL)*

The Nature of Technology	Technology and Society	Design
Standard 1: Students will develop an understanding of the characteristics and scope of technology.	Standard 4: Students will develop an understanding of the cultural, social, economic, and political effects of technology.	Standard 8: Students will develop an understanding of the attributes of design.
Standard 2: Students will develop an understanding of the core concepts of technology.	Standard 5: Students will develop an understanding of the effects of technology on the environment.	Standard 9: Students will develop an understanding of engineering design.
Standard 3: Students will develop an understanding of the relationships among technologies and the connections between technology and other fields of study.	Standard 6: Students will develop an understanding of the role of society in the development and use of technology.	Standard 10: Students will develop an understanding of the role of troubleshooting, research and development, invention and innovation, and experimentation in problem solving.
	Standard 7: Students will develop an understanding of the influence of technology on history.	

Note. Adapted from the International Technology Education Association (ITEA/ITEEA). (2000/2002/2007). *Standards for Technological Literacy: Content for the Study of Technology.* Reston, VA: Author.