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Technical and Saturation Diving

In the world of recreational scuba-diving, you can earn your Deep Diver Specialty Course by paying US$175 and completing two open-water dives down to depths of between 18 and 40 m. For some divers, however, the 40-m limit prescribed by PADI (Professional Association of Diving Instructors) is not deep enough. Fortunately, for those wishing to venture deeper, there is the world of technical diving.

Technical diving[1] is usually defined as diving that includes dives deeper than 40 m, required stage decompression, diving in an overhead environment beyond 40 linear meters from the surface, accelerated stage decompression and/or the use of multiple gas mixtures in a single dive.

Although commercial divers venture deeper, technical divers fall into a special category, since, by utilizing open-circuit equipment, they face infinitely greater risks. In fact, as we shall see in this chapter, it is no exaggeration to say that this elite group of divers work on the ragged edge of technological and physiological knowledge.

The deepest dive achieved by a technical diver using open-circuit scuba is 330 m – a mark set by French diver, Pascal Bernabé, on July 5th, 2005. However, deep as this may be, there is another group of divers who regularly dive even deeper. Saturation (SAT) divers operate at extreme depths as deep as 500 m, breathing exotic cocktails of helium, oxygen, and hydrogen. "Saturation" refers to the fact that the diver's tissues have absorbed the maximum partial pressure of gas possible for that depth due to the diver being exposed to breathing gas at that pressure for prolonged periods.

Here, in Chapter 2, we consider the world of extreme mixed-gas diving. We discuss how revolutionary technologies such as rebreathers will allow technical divers to continue to dive ever deeper and how divers may one day overcome physiological problems such as decompression sickness (DCS) by simply popping a pill.

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[1] The term "technical diving" was first coined in 1991 by Michael Menduno, editor of *AquaCorps*.

TECHNICAL DIVING

Extreme technical diving requires extraordinarily high levels of training, experience, fitness, and logistical support. As of 2009, only eight technical divers are known to have ever dived below 240 m using open-circuit scuba equipment. More people have walked on the Moon and those who understand the perils of this high-risk underwater activity would argue that traveling to the Moon is less dangerous! The deep-diving daredevils of the technical diving community push far into the dark labyrinths of extreme ocean depths. During these extreme excursions, they encounter myriad dangers ranging from disorientation and oxygen toxicity to high pressure nervous syndrome (HPNS) and nitrogen narcosis. Some succumb to the dangers of breathing helium, a gas that can reduce even the most prepared diver to a nervous, quivering wreck. If they survive the gauntlet of these hazards, there are the problems of ascent. If they ascend too quickly, all the nitrogen and helium that has been forced into their tissues under pressure can fizz into tiny bubbles, causing a condition known as the "bends", which may result in paralysis and death.

If you ask recreational scuba-divers about technical diving, you will get different answers. While newly minted scuba-divers may talk about their 20-m dive for months, experienced technical divers frequently plan dives in the 60–100-m depth range. However, there is an elite cadre of technical divers that plan even deeper dives. In the same way as the military seductively draws in new recruits through the imagery of high technology and personal challenge, sport divers are enticed to experience the "new frontiers" afforded by technical diving, but apart from the depth that technical divers reach, there is some disagreement about what the term "technical diving" means. Some divers argue that technical diving is any type of scuba that is considered a higher risk than conventional recreational diving, while others seek to define technical diving by reference to the use of decompression. A minority in the diving community contend that certain non-specific higher-risk factors require diving to be classed as technical diving. PADI, the largest recreational diver training agency in North America, has adopted this as their definition of technical diving:

> "Diving other than conventional commercial or recreational diving that takes divers beyond recreational diving limits. It is further defined as an activity that includes one or more of the following: diving beyond 40 meters, requiring stage decompression, diving in an overhead environment beyond 40 linear meters from the surface, accelerated stage decompression and/or the use of multiple gas mixtures in a single dive."

PADI's depth-based definition is derived from the fact that breathing regular air at pressure causes a progressively increasing amount of impairment due to nitrogen narcosis that may become serious at depths of 30 m or greater. Increasing pressure at depth also increases the risk of oxygen toxicity based on the partial pressure of oxygen in the breathing mixture. For this reason, technical diving often includes the use of breathing mixtures other than air. PADI's mention of decompression alludes

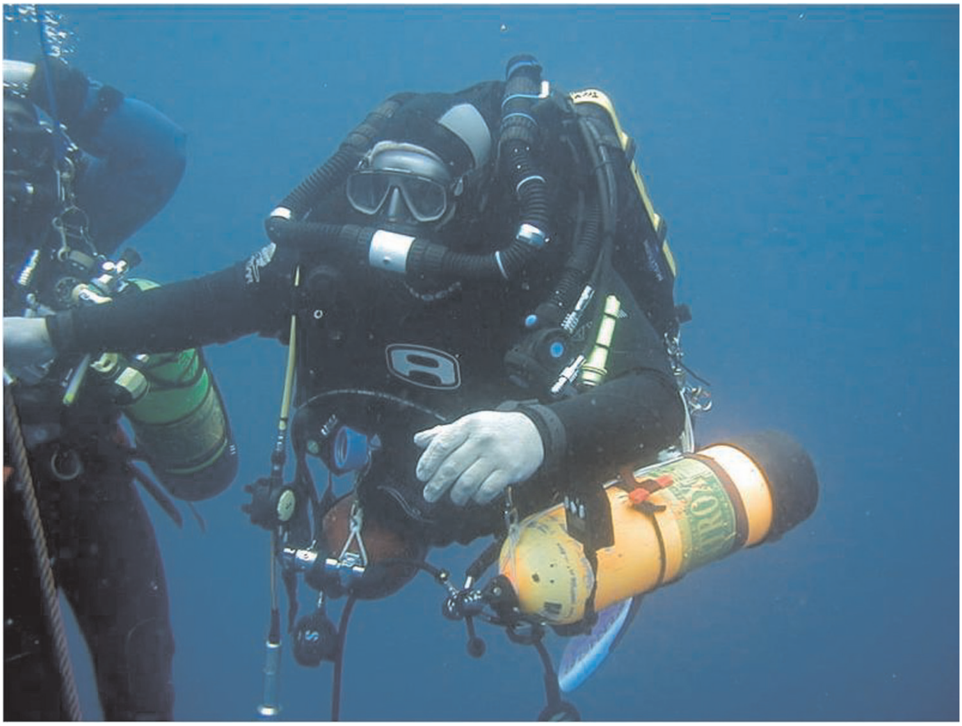

Figure 2.1. Technical diving involves diving beyond the normal limits of recreational diving – a feature reflected in the amount of equipment technical divers need, as shown in this photo. Courtesy Wikimedia.

to the fact that technical dives may be defined as dives in which the diver cannot safely ascend directly to the surface due to a mandatory decompression stop. This type of diving obviously implies a much larger reliance on specialized equipment (Figure 2.1) and training, since the diver must stay underwater until they have completed their decompression stop(s).

It is this reliance upon specialized equipment, combined with the necessity for specialized training, that increases the requirements for risk acceptance, preparation, and level of danger. Additionally, a defining feature that sets technical diving apart from its recreational counterpart is that there is a considerably greater risk and danger from DCS, drowning, oxygen toxicity, nitrogen narcosis, and equipment failure. These risks stem from a number of factors primarily related to the depth, duration, and restrictions of the dives that technical divers perform. A classic example is decompression. Technical diving almost inevitably involves decompression diving, which, in itself, introduces a significant risk.

Decompression sickness

As soon as a diver submerges beneath the water, he/she begins to incur a decompression debt. The debt is created by a greater amount of gases dissolving in the blood and cells as the greater depth causes an increase in the partial pressure relative to the conditions at the surface, where the pressure is 1 atmosphere. When the diver begins his/her ascent, these gases leave solution and may cause life-threatening bubbles in the bloodstream and tissues. The amount of dissolved gas in the blood and other tissues is a factor of time and pressure. The dissolution of gas is not instantaneous, but happens over time until equilibrium is reached. This means that even a shallow dive to 10 m for a long period of time can cause the dissolution of a substantial amount of gas as a deep dive for a short period of time. The limits to deep diving are set by factors related to the increasing mass of the water column above the diver as the diver descends. Decompression problems occur during the ascent phase of a dive. The diluent gas in the divers' breathing mixture dissolves in the tissues in proportion to the solubility of the gas in tissues and the partial pressure of the diluent gas. During the ascent, the partial pressure of the diluent gas decreases, which causes a decreasing volume of gas to remain in solution in the tissues. The rate at which this occurs is determined by the rate of ascent and is perhaps the most important aspect of any dive. To ensure that the excess diluent gas can be eliminated via diffusion across the epidermal tissue, lungs, or other mucous membrane body surfaces, with the residual gas remaining in solution, the diver must ascend at a prescribed rate. If the ascent rate is exceeded, gas bubbles may form in the diver. When the gas bubbles are large and numerous, or located in particularly vulnerable tissues such as the spinal cord and joints, they may cause a painful and potentially seriously debilitating condition known as DCS. A diver at the end of a long or deep dive may need to perform decompression stops (Figure 2.2) to avoid DCS. This is because metabolically inert gases in the diver's breathing gas, such as helium, are absorbed into body tissues when breathed under high pressure during the deep phase of the dive. These dissolved gases must slowly be released from body tissues by stopping at various depths during the ascent to the surface. In the last decade, most technical divers have favored deep first decompression stops because research suggests this will reduce the risk of bubble formation before the long shallow stops.

Compounding the problem of decompression is the challenge posed by breathing gas mixtures. To reach the depths attained during technical diving, divers must use exotic gas blends. This is because breathing a mixture with the same oxygen concentration as air (roughly 21%) at depths greater than 55 m results in a rapidly increasing risk of severe symptoms of oxygen toxicity – a syndrome that may prove deadly. The first sign of oxygen toxicity is often a convulsion without warning. Occasionally, the diver may experience warning symptoms prior to the convulsion. These symptoms may include visual and auditory hallucinations, nausea, twitching, irritability, and dizziness. More often than not, a convulsion at depth is usually fatal because the regulator will fall out and the diver will drown.

Increasing depth also causes nitrogen to become narcotic, resulting in a reduced ability to react or think clearly – a syndrome known as *nitrogen narcosis*. By adding

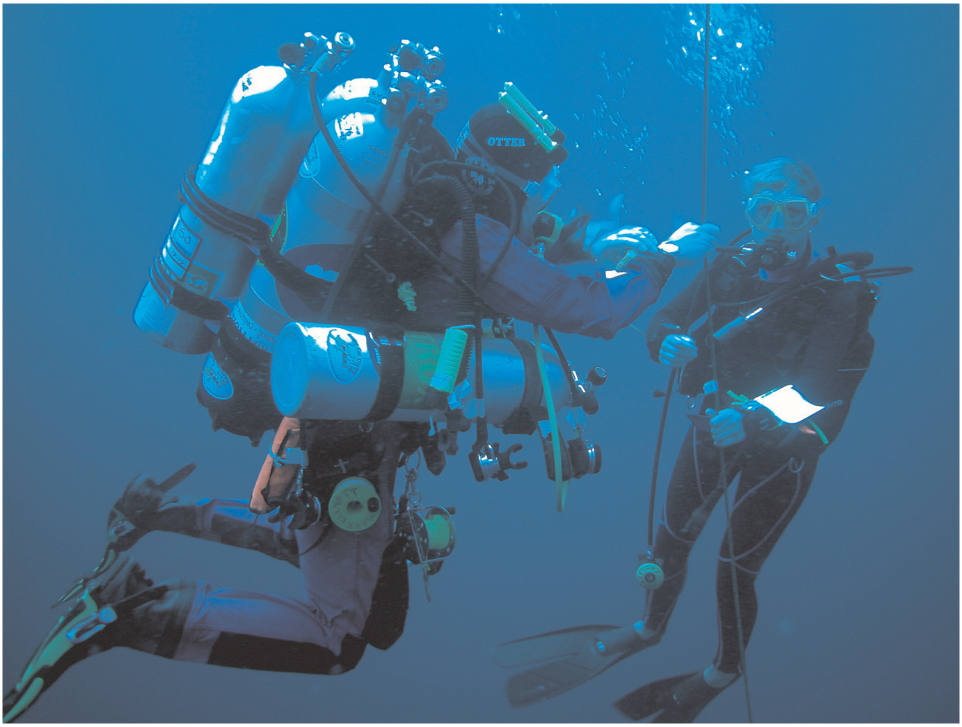

Figure 2.2. A technical diver performing a decompression stop. A "deco" stop is a period of time a diver must spend at constant depth following a dive to eliminate absorbed inert gases from the body to avoid decompression sickness. A technical diver at the end of a long or deep dive may need to perform multiple "deco" stops at various depths during the ascent to the surface. In recent years, technical divers have increased the depth of the first stops, to reduce the risk of bubble formation before long shallow stops. Courtesy Mark Ellyat.

helium to the breathing mix, divers can reduce these effects, as helium does not have the same narcotic properties at depth. These gas blends can also lower the level of oxygen in the mix, thereby reducing the danger of oxygen toxicity. Once the oxygen fraction is reduced to below 18%, the mix is known as a hypoxic mix, since it does not contain sufficient oxygen to be used safely at the surface. Another technique employed by technical divers to reduce the risk of nitrogen narcosis is to breathe enriched oxygen breathing gas mixtures during the beginning and ending portion of the dive. For example, while at maximum depth, it is common to use a gas known as "trimix", which adds a fraction of helium to and replaces nitrogen in the diver's breathing mixture. Another tactic designed to reduce the time required to rid themselves of most of remaining excess inert gas in their body tissues and to reduce DCS risk is to use pure oxygen during the shallow decompression stops.

One gas that technical divers use to avoid nitrogen narcosis is heliox, a mixture of helium and oxygen. It is used as a breathing gas only for extreme diving depths and the exact gas fractions in the mixture are determined by the intended depth. For example, imagine a diver making a dive to 100 m. The pressure at 100 m is 11 atmospheres (pressure increases at a rate of 1 atmosphere for every 10 m of depth, so at 100 m, the pressure exerted upon the diver is the atmospheric pressure *plus* the pressure of 10 atmospheres), or 11 *bar*, to use the diving vernacular. Because the diver knows that oxygen toxicity occurs at a partial pressure of 1.6 bar, he/she must choose a gas blend that will have a lower oxygen partial pressure than 1.6 bar. To err on the side of caution, he/she might choose a mixture comprising 14.5% oxygen and 85.5% helium. This oxygen fraction would minimize the chance of oxygen toxicity, since the partial pressure at 100 m would be 1.595 bar ($pO_2 = 0.145 \times 11 = 1.595$ bar). While heliox is an easy blend to manipulate, perhaps its greatest attraction to technical divers is that it does not contain any nitrogen, so the risk of DCS is eliminated. However, one shortcoming of heliox is that helium is a highly efficient conductor of heat so a diver breathing a helium blend will chill far more quickly than an air-breathing diver. But, of course, an air-breathing diver is limited to dives of only 40 m! Unfortunately, while heliox is a favorite gas blend among technical divers, the gas is expensive and, at present, most of the world's helium reserves are in Texas and those reserves are running low. These circumstances have forced technical divers to consider other blends such as hydrox. If any blend can be considered the perfect mix for technical diving, it may be hydrox, which is a blend of hydrogen and oxygen. Although the mixture is still in the experimental stages, it has produced good results, since it is easy to breathe, incurs no DCS risk, and the gas conducts heat slowly, unlike helium. Its only real flaw comes from the extremely flammable nature of hydrogen – a stigma that has followed the gas since the *Hindenburg* disaster.

Another popular gas mix that extends depth considerably is trimix, a blend comprising oxygen, nitrogen, and helium. To create trimix, the helium is added as a diluent for the nitrogen content and the oxygen level is also reduced, depending on the depth desired. With the reduced levels of nitrogen and oxygen, the maximum safe depth can exceed 100 m. The downside to trimix is that unless the oxygen content is kept between 18 and 21%, a travel gas[2] is usually required for descending to the safe breathing zone. Inevitably, this means extra cylinder requirements and gas planning, but this is all part and parcel of technical diving so is considered a minor inconvenience.

So far, we have discussed the risks of technical diving and the gas mixes required. Before we can take a step into the future of this cutting-edge sport, we must now consider the equipment. Technical divers use a truly extraordinary amount of equipment (Figure 2.3). In fact, witnessing a diver gearing up for a deep mixed-gas dive is akin to watching an astronaut prepare for a spacewalk. In addition to the standard drysuit, the modern-day technical diver is encumbered by two or three of everything, highlighting a (necessary) compulsion for redundancy that further underlines the dangerous nature of the activity. As you can see in Figure 2.3,

[2] A travel gas is simply one that is breathed until the target depth is achieved, whereupon a gas switch is performed and the diver begins breathing the trimix.

Figure 2.3. Here, you get some idea of the set-up required for technical diving. The tech-rig pictured is a good illustration of the redundancy required to safely perform technical dives and also the amount of gas that needs to be carried to perform all the decompression stops. Courtesy Mark Ellyat.

technical divers usually carry at least two cylinders, each with its own regulator. In the event of a failure, the second cylinder and regulator act as a backup system. Technical divers therefore increase their supply of breathing gas by connecting multiple high-capacity diving cylinders. The technical diver may also carry additional cylinders, known as *stage bottles*, to ensure adequate breathing gas supply for decompression with a reserve for bail-out in case of failure of their primary breathing gas. The amount of equipment worn by the diver in Figure 2.3 is typical for a technical diver and while it may appear unwieldy, the set-up is fairly standard.

EXTREME DIVING

Once a diver has chosen his gas mix, decided which equipment configuration he/she is going to use, and planned the dive, all that remains is the dive itself. Perhaps the best way to explain what happens during a technical dive is to follow the exploits of an extreme technical diver during one of the deepest dives ever recorded. What follows is an account of Mark Ellyat's then world-record dive to 313 m in December 2003.

Figure 2.4. In 2003, Mark Ellyat broke the record for the world's deepest dive using scuba equipment, reaching 313 m off the coast of Phuket, Thailand, following a dive lasting 7 hr. For those interested in exploring the extreme side of technical diving, Mark has published a book – *Ocean Gladiator* – that describes his exploits deep beneath the ocean. Courtesy Mark Ellyat.

One thousand feet (305 m) was long regarded as the 4-min mile of open-circuit scuba-diving and still marks the gold standard for those in the technical diving community. Those attempting depth records using open-circuit scuba usually do so in fresh-water sink holes, since these environments provide reasonably predictable conditions, which makes the staging of cylinders and equipment a little easier. However, even when diving in a sink hole, the technical diver still has to consider huge differences in surface and bottom temperatures and unpredictable currents. The record Ellyat (Figure 2.4) was attempting to break was set by John Bennett in November 2001. Bennett was no stranger to the extraordinary demands of extreme deep diving. In June 2000, he had established a world depth record of 254 m in the warm waters off Puerto Galera in the Philippines. However, setting a world record was not enough for Bennett, who immediately began planning an even deeper dive that would break the thousand-foot barrier. He achieved his goal by plunging to 308 m in November 2001. In March 2004, Bennett went missing in South Korea in just 45 m of water and was later declared dead.

Like Bennett, Ellyat's goal was a world-record dive, but it almost did not happen. In February 2003, the diver with almost 3,000 dives under his weight belt almost

Figure 2.5. Mark Ellyat kitted out in the equipment he used to break the record for the world's deepest dive. Courtesy Mark Ellyat.

made his last dive during a practice dive to 260 m; Ellyat's decompression schedule proved inadequate and he sustained serious injuries. The doctor advised him never to dive again, which, to any extreme sportsman, is akin to waving the proverbial red rag to a bull. Ellyat ignored the medical advice and started planning his attempt on Bennett's record.

Embarking upon such a venture was something akin to planning a space mission, requiring months of planning just to configure the equipment, the complexity of which was formidable. The first problem faced by any diver attempting to dive so deep is the sheer number of cylinders required (Figure 2.5) to carry the huge amounts of gas required for what may be a dive lasting 10 hr or more. Whereas a recreational diver only has to worry about a single cylinder on his/her back, for the Mark Ellyats of the diving world, cylinders must be brought along for the descent, the bottom (for decompression), drysuit inflation, and decompression stops during the ascent. For this record attempt, Ellyat wore an Otter "Velvet-Skin" purple-colored drysuit, constructed of a special membrane material designed to be strong but flexible. Because he needed to carry multiple steel cylinders on his back, Ellyat had to use special dual bladder wings to provide sufficient buoyancy.

Another key part of any successful dive is the support team. For his record-breaking dive, Ellyat employed the services of 14 experienced deep divers in addition to a paramedic for any medical contingencies. In the week leading to the dive, the support team busied themselves with briefings, discussions of dive profiles, potential gas problems, abort scenarios, and setting the depths for the support divers. Once the dive profile had been approved, some team members went about assembling the dive platform and fine-tuning contingency evacuation plans while others started the complex process of mixing Ellyat's gas blends.

Ellyat's dive site was on the edge of the continental shelf at 450-m depth, 60 km offshore from Phuket, Thailand – a site chosen due to the high quality of medical support and availability of military hyperbaric chambers. If Ellyat had a problem, he knew he could be at a hyperbaric facility quickly thanks to a 600-horsepower engine bolted to the back of one of the boats. The descent proceeded smoothly until 250 m, when Ellyat noticed minor HPNS symptoms, although he was not sure whether the shakes were helium-induced or the result of the icy water. On reaching 300 m, he noticed the contents gauge showed the turn-around pressure but he continued on down to 313 m. The descent had taken just 12 min. At the bottom of the dive, the water temperature was just 3°C. Spending no more than 60 sec there, he collected a marker to verify his record-breaking depth and began his ascent. In common with Bennett, Ellyat's ascent profile was based on intuition and knowledge of the emerging science of deep decompression that suggests decompression benefits can be gained by stopping deep for short periods of 30 sec or less. However, too many stops below 200 m may add to the overall decompression penalty. The problem is no one really knows for sure. Ellyat's ascent rate on leaving the bottom was a conservative 18 m per minute. He completed the deep stops without incident, meeting his first support diver at 90 m, where he was handed a cylinder of trimix. After completing his 90-m decompression stop, Ellyat continued on to complete more stops at 75 and 60 m. The ascent took 6 hr and 36 min, during which Ellyat used 24 cylinders brought down to him by support divers.

Ellyat's descent to 313 m was an epic dive, and one that blurred the distinction between commercial diving and the sport diving community. As the description of Ellyat's dive illustrates, venturing into the realm of decompression and mixed gas requires far more training, equipment, and knowledge of operational disciplines than most technical divers have or are willing to acquire. Furthermore, diving to extreme depths using cumbersome cylinder rigs and multiple gas mixes is a dangerous pursuit, as evidenced by the death of John Bennett and several other divers in the technical diving community. There has to be a better and safer way.

REBREATHERS

The equipment that may represent the future of technical diving is the rebreather (Figure 2.6), a breathing system enabling the diver to retain and reuse some or all of the expired gas. The problem with open-circuit (so-called because once the gas leaves the diver, it is no longer part of the breathing cycle) scuba is that the diver typically only uses about a quarter of the oxygen in the air that is breathed in. The rest is exhaled along with nitrogen and carbon dioxide. It is a very wasteful and inefficient

Figure 2.6. The Evolution is typical of the current generation of closed-circuit rebreathers. Compact, streamlined, and weighing only 24 kg, diving with this CCR is a dream compared with the cumbersome tech-rigs that are usually associated with technical diving. Photo John Bantin. Courtesy Ambient Pressure Diving.

system and as depth increases, the inefficiency of the open-circuit system is compounded, since, because of the increased pressure, even more gas is lost with each exhaled breath. For example, at a depth of 30 m, the average open-circuit scuba-diver breathes at a rate of 100 l per minute, 98.9% of which is just bubbled away! In contrast, a closed-circuit rebreather (CCR) diver's metabolic consumption at 30 m is only 1 l per minute! Another way of thinking about this is to imagine a standard scuba cylinder that contains enough gas to sustain an average resting person for about 90 min at the surface. The same cylinder will last only 45 min 10 m underwater, and less than 10 min at a depth of 90 m. But if that same cylinder were filled with oxygen and used to supply a CCR, the diver could theoretically stay underwater for *2 days* – regardless of the depth!

Another advantage of CCRs is "decompression optimization". Because a CCR maintains the oxygen concentration in the breathing gas at its maximum safe value throughout the dive, the non-oxygen portion of the breathing gas (the part that determines decompression requirements) is maintained at a *minimum*. Not only does

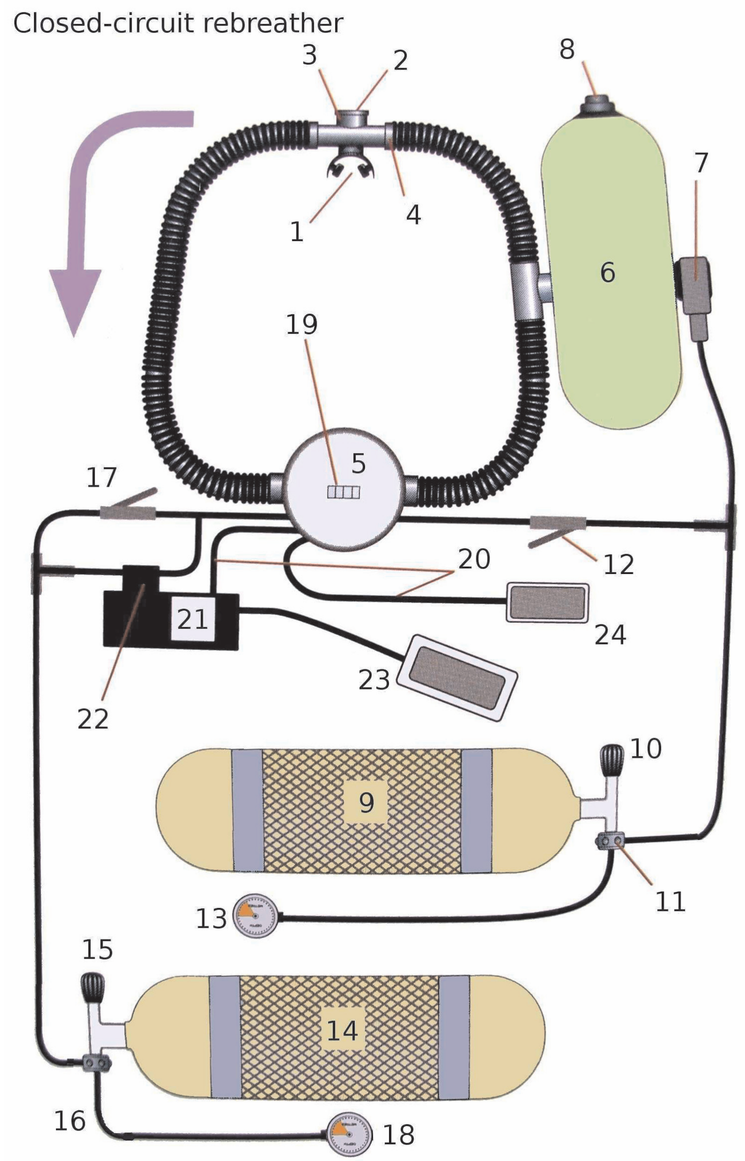

Figure 2.7. Schematic of a closed-circuit rebreather. Key: (1) Mouthpiece (2) Closing of mouthpiece (3) Return valve (to outlet) (4) Return valve (to inlet) (5) Scrubber (6) Counterlung (7) Diluent valve (8) Overpressure valve (9) Diluent cylinder (10) Diluent tap (11) Diluent control (12) Manual diluent inflator (13) Diluent manometer (14) Oxygen cylinder (15) Oxygen tap (16) Oxygen control (17) Manual oxygen inflator (18) Oxygen manometer (19) Oxygen cells (20) Cable (21) Electronic regulator (22) Electronically controlled valve (23) Primary display (24) Secondary display. Courtesy Wikimedia.

this permit the diver to stay longer at depth without incurring a decompression penalty, but it also speeds up the decompression process if a penalty is incurred.

Another drawback of open-circuit scuba is that the deeper you dive, the more rapidly you use up air, so a dive's maximum duration is determined by depth and the number of cylinders on your back. At the end of the day, a lot of the oxygen divers take with them is wasted, but rebreathers change this equation by *re-circulating* the exhaled gas for reuse and simply add a little oxygen to replace the oxygen that was consumed. The carbon dioxide is removed by a process called "scrubbing", which is achieved by an assembly that uses a soda–lime mixture (sodium hydroxide and calcium hydroxide) to absorb the carbon dioxide.

At first glance, a rebreather looks like something out of a science-fiction movie, but a closer look reveals that the system (Figure 2.7) makes sense and when you begin to understand how this system works, you being to appreciate how this different way of diving has the potential to open up new frontiers underwater. To get a better understanding, let's take a look at the components common to rebreathers.

One key element is some means to remove expired carbon dioxide from the breathing gas as it is recycled. Carbon dioxide is usually given off at a level of about 0.8 times the amount of oxygen consumed, so a rebreather has to remove about 1 l of carbon dioxide for each liter of oxygen utilized. Most rebreathers remove carbon dioxide by passing the expired gas through a canister (the scrubber, Panel 2.1) filled with chemical absorbent.

Panel 2.1. Sofnolime

Rebreathers purify breathing gas by "scrubbing". The chemical most often used to scrub the gas is soda–lime. Soda–lime – *Sofnolime* is a commercial diving product – is mostly slaked lime mixed with small amounts of more strongly based pH chemicals to help speed up the process. Some formulations also contain specific amounts of water to kick-start the chemical process. Carbon dioxide exhaled by the diver mixes with the water to form weak carbonic acid. The carbonic acid reacts with the soda–lime to form chalk, a stable solid compound that binds the carbon dioxide and removes it from the breathing gas.

Another important component is some sort of variable volume container to capture the diver's exhaled breathing gas. This is achieved by the "counterlung" (Figure 2.7), a sort of breathing bag for the diver to breathe in and out of. In addition to the counterlung, the rebreather hardware must include absorbent canisters, a means of regulating gas flow, a housing, gas storage, and a mouthpiece. Regulation of the rebreather's counterlung is affected by changes in depth. As depth changes, the rebreather unit must adjust to both a change in the gas volume and a change in the oxygen fraction in order to maintain counterlung volume and a constant partial pressure of oxygen. Consequently, ascents cause a release of bubbles and descents require addition of gas to maintain system volume, which means too many depth changes may deplete the gas supply, even if the diver does not use gas.

If you take a look at Figure 2.7, you will see the elements through which air passes during what is called the breathing loop. These elements include the mouthpiece, breathing hoses, counterlung, and scrubber (because the gas is contained inside the diver's lungs during the recycling process, the diver is also included in the loop).

While all rebreathers incorporate these key elements, there is much variability in design, each category having advantages and disadvantages, one of which is cost. A typical rebreather will set you back as much as US$20,000, not to mention the extensive additional training and certification you will need to use it. But, as we shall see, a rebreather does for scuba-diving something like a hybrid engine does for a car: it provides much greater fuel efficiency and while that may not seem like a big deal on the road, underwater it can make all the difference in the world.

Types of rebreathers

There are three main categories of rebreathers: oxygen closed-circuit, semi-closed-circuit and mixed-gas closed-circuit. Oxygen closed-circuit rebreathers, commonly referred to as oxygen rebreathers, are the most basic and least expensive rebreather design. As the designation suggests, the breathing gas is 100% oxygen and since there is no inert gas in the breathing loop, the diver does not have to worry about performing any decompression stops. In an oxygen rebreather, oxygen is added to the system through a special valve designed to maintain a constant volume of gas in the breathing loop. As the volume decreases, oxygen is added to compensate. It sounds simple, and it is, but the disadvantage of oxygen rebreathers is that the diver is breathing 100% oxygen, which means the deepest dive can be no deeper than 6 m! Deeper than this and the diver increases the risk of oxygen toxicity. However, because they are bubble-free systems, oxygen rebreathers are used extensively by the military to conduct covert shallow-water operations.

To permit divers to dive deeper, it is necessary to dilute the oxygen with an inert gas. Semi-closed rebreathers (SCRs) do this by utilizing enriched air nitrox gas (EANx) as the diluent gas. EANx is an oxygen–nitrogen blend containing a higher oxygen percentage than normal air. Although the breathing loop of an SCR is similar to an oxygen rebreather, there are some differences to accommodate the use of the EANx. One difference is the inclusion of an overpressure valve that vents gas to ensure the breathing loop is maintained at ambient pressure. Another feature is a special valve that injects the breathing gas at a concentration that overcomes the diver's metabolic oxygen consumptions. Thanks to these extra features, SCRs permit a four-fold increase in gas economy compared to open-circuit scuba and allow divers to perform dives as deep as 40 m. They are also relatively simple and inexpensive, which is why they are the most widely used rebreather by recreational divers. However, despite its versatility, the SCR design limits the diver to just 40 m, which hardly makes it a useful tool for underwater exploration. Fortunately, there is another type of rebreather that may ultimately prove to be a powerful tool in extending the range of the technical diver.

The closed-circuit rebreather

Mixed-gas CCRs are the most versatile diving units on the market today, since they offer the diver a wide depth range, long duration, optimal gas loading, and high gas efficiency. A CCR improves upon the efficiency of the SCR by injecting oxygen only when it is required to compensate for the diver's actual metabolic consumption. This is achieved by measuring the partial pressure of oxygen in the breathing loop and injecting oxygen to maintain the partial pressure. In this system, all the exhaled air is retained within a closed loop (Panel 2.2). The air is then filtered, refreshed, and recycled back to the diver for further use – a design that provides extraordinary diving endurance when compared with traditional scuba.

Panel 2.2. The closed loop

1. Exhaled gas leaves the diver's lungs and is routed into a one-way loop beginning at the unit's exhale counterlung.
2. The exhaled gas is routed, via a water-trap, into the scrubber unit, where it passes upwards through a Sofnolime filter stack, which scrubs the breathing gas of carbon dioxide.
3. Inside the mixing chamber, three independent oxygen sensors measure oxygen pressure and the partial pressure of oxygen in the gas. If the oxygen's partial pressure drops below a threshold (termed the "setpoint"), an oxygen controller opens an oxygen valve to bring the partial pressure to the threshold.
4. Scrubbed breathing gas returns via a second water-trap to the inhale counterlung ready for use in the next breathing cycle.

Because the CCR adds only a small volume of oxygen to the system at a time, the diver only has to take along a small oxygen cylinder and the only limitations on the depth and duration of a dive are the diver's metabolic rate and oxygen partial pressure preference. If the diver is diving to 46 m or shallower, the diver will take along a second cylinder holding diluent gas, while for deeper dives, they will usually use a trimix blend. Because the diver is breathing the ideal gas mixture at every depth, no-decompression limits are much longer. The only disadvantage, other than the cost (US$10,000 and up!), is the extensive training required, since divers must become intimately familiar with all the quirks and eccentricities of the particular system they are diving. The training is particularly important because the complex design means a mixed-gas CCR has the greatest risk of failure due to user error and/ or mechanical malfunction. However, recent advances in rebreather design mean that while the systems continue to be sophisticated machines, a properly trained diver can minimize the risk. A good example of such a system is the Evolution CCR.

The Evolution closed-circuit rebreather

Compact, light, and streamlined, the Evolution (Figure 2.8) is a diver's dream thanks to the system's redundancy and the future-proofed electronics package that lie at the heart of this revolutionary CCR. The Evolution's Vision versatile electronics package is as simple or as complicated as the diver wants to make it. Because it comes installed with six memorized gas mixes, it is possible to program gases for an entire diving season or simply customize them for a single dive. The computer is also programmed with Gradient Factors, enabling the diver to customize ascent profiles based on dive fitness, environment, and age. Selecting the Gradient Factors enables the diver to select a dive profile based on DCS risk. For example, if a diver selects a low Gradient Factor, by deciding to conduct deep decompression stops, he/she simply selects a number between 5 and 30 – the lower the number, the lower the risk.

Diving with a CCR as advanced as the Evolution after spending years using traditional rebreathers is akin to making the jump from flying a Cessna to flying a Citation jet. Part of the reason is the level of control that is at the diver's fingertips. In addition to a primary display and head-up display (HUD), the Evolution has built-in decompression algorithms and two independent control systems: one Master

Figure 2.8. The Evolution closed-circuit rebreather. Photo John Bantin. Courtesy Ambient Pressure Diving.

and one Slave, which serves as a backup. System redundancy is achieved by each controller having its own power supply – a feature enhanced by the operation of the Master and the Slave, since the Slave not only monitors the Master controller, but also checks the partial pressure of oxygen and gives the diver warnings if the oxygen level deviates from the setpoint. This is important because it affects the length of time a diver can actually dive. You see, the length of time a diver can spend underwater depends on a number of factors, ranging from the system's central nervous system (CNS) toxicity clock, the life of the carbon dioxide scrubber, and, of course, the gas supply. To prevent the diver from suffering the effects of oxygen toxicity, the Evolution is fitted with a default setpoint of 1.3 bar, which is limited to 3 hr per day, depending on what level the setpoint is selected. Another factor that determines the dive duration is the Sofnolime, which is depleted depending on the diver's production of carbon dioxide, water temperature, and work rate. However, even a hard-working diver using 2 l per minute would be able to dive for 5 hr using the Evolution's 2-l cylinder, which provides 400 l of oxygen.

In addition to providing extended dive duration, the Evolution also ensures a high degree of safety thanks to myriad intuitive warning systems. A solid green light indicates all systems are functioning as they should. If the diver sees any other color light, it is a warning to check the handset. In the unlikely event the handset fails, the diver can still rely on the information scrolling across the HUD, which will tell them about everything from battery life to the partial pressure of oxygen. In fact, there are three independent monitoring systems and displays available to the diver – a design that ensures a high level of system redundancy. Helping make sense of all the information is the HUD that is split into two displays (one for each oxygen controller) comprising just two pairs of lights, the brightness of which can be changed in accordance with ambient light conditions. When the system is functioning normally, the HUD shows two solid green lights, one for each oxygen controller. If the diver encounters a problem, a buzzer is accompanied by flashing red lights.

Another key safety feature is the Scrubber Monitor, which warns the diver in advance of increasing carbon dioxide concentration. The Scrubber Monitor is particularly noteworthy because until the advent of the Evolution, a reliable scrubber duration warning system had proven elusive. Utilizing an array of digital temperature sensors, the Scrubber Monitor checks the temperature profile of carbon dioxide-laden exhaled gas in real time and compares it with other sensors. This information is then displayed on the wrist-set to show the hot sections of the scrubber.

With all this information, it is hardly surprising that the Evolution (Figure 2.9 and Table 2.1) comes complete with a computer-link capability enabling divers to download up to 9 hr of recorded dive data, which include the depth–time profile, real-time partial pressure of oxygen, scrubber temperatures, surface interval, decompression, ambient temperature, and even battery voltages.

Despite their sophistication and cost, CCRs such as the Evolution have been embraced by the technical diving world because they offer a means of truly exploring the underwater frontier and, in time, they will undoubtedly become an important

Figure 2.9. The Evolution showing the harness, wings, and hose. The system is an electronics-driven fully closed-circuit constant partial pressure of oxygen rebreather that provides the diver with a host of diving information via a heads-up display. It costs about US$10,000. Photo John Bantin. Courtesy Ambient Pressure Diving.

tool for those who can afford the cost and necessary training. Yet, despite being such a powerful tool for technical divers of the future, CCRs such as the Evolution are limited to a maximum depth of 160 m.[3] While this may be deep enough even for technical divers, there are always those who really want to push the limits. For these daredevils, there is saturation diving.

SATURATION DIVING

"Saturation" simply refers to the fact that the diver's tissues have absorbed the maximum partial pressure of gas possible for that depth as a result of the diver having been exposed to breathing gas at pressure for a prolonged period. This is significant because once the tissues become saturated, the time to ascend from depth

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[3] On August 21st, 2003, German divers Chris Ullmann, Manfred Führmann, and Volker Clausen claimed a new depth record using closed-circuit breathing dive equipment after reportedly descending to 224.5 m.

Table 2.1. Evolution technical specifications.

Weight	26 kg	Weight of Sofnolime	2.5 kg
Absorbent duration	3 hr (4°C)	Oxygen cylinder	1 × 2 l
Diluent cylinder	1 × 2 l	Atmospheric range	650–1080 mbar
Buoyancy compensator	Wing style – 16 kg	Counterlung volume	Medium: 11.4 kg Large: 14 kg
Cylinders	Two 2-l steel cylinders: one oxygen, one diluent		
First stage (oxygen)	Intermediate pressure: 7.5–8.0 bar		
First stage (diluent)	Intermediate pressure: 9.0–9.5 bar		
Oxygen control	Two oxygen pressure setpoints		
Oxygen setpoint range (low)	0.5–0.9 bar	Oxygen setpoint range (high)	0.9–1.5 bar
Oxygen warning level (low)	0.4 bar	Oxygen warning level (high)	1.6 bar

Depth limits

Depth (m)	
40	Maximum depth with air diluent
100	Maximum depth for which all rebreather parameters proven
110	Depth at which work of breathing has been tested using trimix
150	Maximum depth at which work of breathing has been tested with heliox as diluent
160	Depth at which all components are pressure tested

and to decompress safely will not increase with further exposure. This means that SAT diving enables divers to live and work at depths greater than 50 m for days or even weeks at a time. It is a type of diving that allows for greater economy of work and enhanced safety for the divers, since, after working in the water, the divers can rest and live in a dry pressurized habitat on the ocean floor at the same pressure as the work depth. The diving team is compressed to the working pressure only once, and decompressed to surface pressure once. From an operational perspective, there are two principle factors in SAT diving: the depth at which the diver's tissues become saturated (storage depth) and the vertical range over which the diver can move (excursion depths).

SAT divers (Figure 2.10) usually live in a surface chamber known as a Deck Decompression Chamber (DDC) at a "storage" pressure that is shallower than the diver site. If the chamber is on a surface ship, the divers transfer to a Personnel Transfer Capsule (PTC) through a mating hatch in the DDC, and the PTC is lowered to the dive site. Figure 2.11 shows a typical SAT system, which usually comprises a DDC, transfer chamber, and a PTC, which is commonly referred to in

Figure 2.10. A saturation diver works outside the Aquarius habitat off the coast of Florida. Courtesy NASA.

commercial diving parlance as the diving bell. The entire system is usually placed on a ship or ocean platform and is managed from a control room, where depth, chamber atmosphere, and other system parameters are monitored.

The diving bell transfers divers from the SAT complex to the work site. Usually, it is mated to the complex utilizing a removable clamp and is separated by a trunking space, which is a kind of tunnel through which divers transfer to and from the bell. Upon completion of underwater operations, the SAT diving team is decompressed gradually back to atmospheric pressure by the slow venting of system pressure at an average of 15 m per day, traveling 24 hr a day, depending on the depth, length of time at depth, and the breathing gas. Thus, the SAT process involves only one ascent, thereby mitigating the time-consuming and comparatively risky process of in-water, staged decompression normally associated with traditional diving operations. From their SAT complex, divers use surface-supplied umbilical diving equipment,

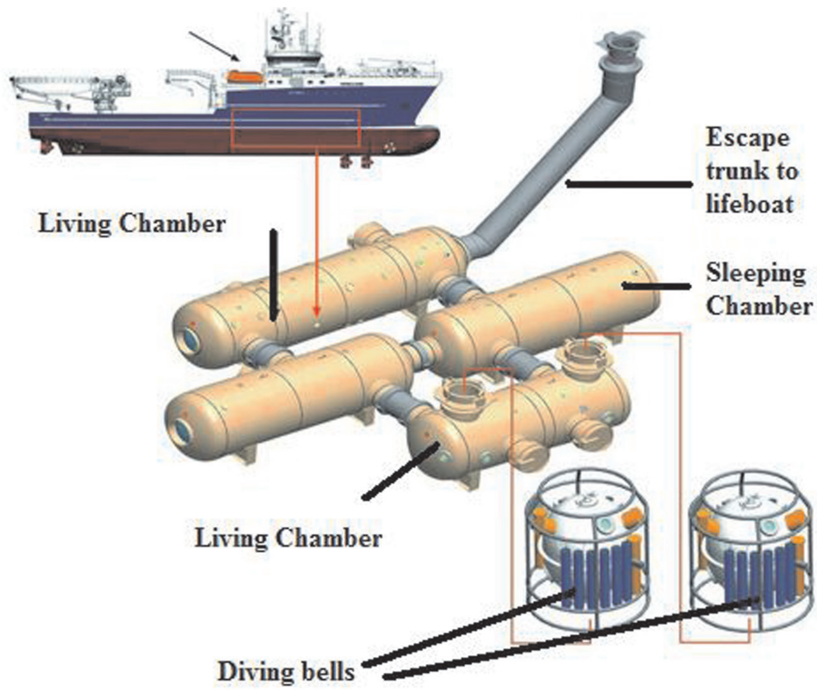

Figure 2.11. The layout of a typical saturation diving system showing the surface support vessel and living quarters.

utilizing breathing gases such as helium and oxygen mixtures. The gases are stored in large-capacity, high-pressure cylinders and are plumbed to the control room, where they are routed to supply the system components. The diving bell is fed via a large umbilical that supplies breathing gas, electricity, communications, and hot water. The bell is also fitted with exterior-mounted breathing gas cylinders in the event of a contingency. While in the water, the divers use a hot-water suit to protect against the cold. The hot water comes from boilers on the surface and is pumped down to the diver via the bell's umbilical and then through the diver's umbilical.

SAT diving might satisfy a diver's need for adventure but it is not a healthy way to earn a living. Long-term exposure to breathing gas under high pressure may cause aseptic bone necrosis, which is why commercial divers usually have X-rays taken at regular intervals. Then there are the dangers of breathing gas at extreme pressure to consider. For example, in the North Sea, commercial divers operate at depths of up to 500 m. At this depth, they breathe either a combination of hydrogen and oxygen (hydrox) or an exotic blend of hydrogen, helium, and oxygen (hydraliox). At these extreme depths, divers are susceptible to HPNS, insomnia, and bouts of extreme fatigue, which is the result of breathing gas that is as much as 50 times as dense as air on the surface. Divers usually describe the sensation as trying to breathe soup!

The complexity of diving to such extreme depths is compounded by the decompression requirement. For divers breathing helium–oxygen, for example,

Table 2.2. Saturation decompression.

Rate	*Depths*
1.8 msw/hr	From 480 to 60 msw
1.5 msw/hr	From 60 to 30 msw
1.2 msw/hr	From 30 to 15 msw
0.9 msw/hr	From 15 to 0 msw

pressure reduction must follow a very slow schedule (Table 2.2), which means for a diver working at 500 m for 2 weeks, it may take as long as a month to decompress to the surface!

Diving physiologists attempt to reduce the decompression penalty by having divers breathe specialized gas mixtures at various depths during the decompression phase, but despite carefully calculating gas uptake and elimination speeds, and despite factoring in tissue-blood gradients, the length of time to decompress from depths of several hundred meters is still measured in weeks. In fact, the decompression time may be even longer because if the diver experiences DCS symptoms, the diver must be recompressed until the symptoms are relieved and then decompression reinitiated more slowly. Decompression is thus inherently not only expensive, but also dangerous because the diver's tissues must remain continuously in a supersaturated state in order to eliminate the burden of excess diluent gas. Also, DCS cannot be predicted or prevented with absolute certainty because of its probabilistic nature and because each diver reacts differently. The same diver may have a different reaction at different times because of myriad factors ranging from dehydration to fitness and stress. Therefore, the decompression rate necessary to prevent DCS for any individual can only be an approximation based on prior general experience because all the risk factors involved in the off-gassing rate for a given person are not and can never be known. Inevitably, a method for shortening decompression would reduce a time of great personal risk to the diver as well as reducing expenses of the dive operation. Such a method would represent the future of SAT diving and it is discussed here.

Biochemical decompression

The notion of biochemical decompression was first proposed by Dr. Lutz Kiesow, a leading scientist at the Naval Medical Research Institute (NMRI) who suggested using hydrogenase to cause biochemical decompression. According to Dr. Kiesow's idea, a diver would breathe a gas blend containing hydrogen and oxygen. The diver would then be supplemented with a hydrogenase enzyme, which is found in some bacteria. The hydrogenase enzyme would convert the hydrogen to some other molecule – a process that would ameliorate the diver's burden of excess diluent gas during the ascent phase, thereby reducing the decompression time. Subsequent research attempted to put Dr. Kiesow's concept into action by putting purified hydrogenase into red blood cells directly. The scientists found it was possible to encapsulate the enzyme into red blood cells, but they could not devise an animal model in which to test the cells. The concept of incorporating the hydrogenase into the blood was not pursued because even if the enzyme could be packed into the blood cells and be injected into a diver, the cells could only be circulated for a few weeks before the red blood cells died naturally and were eliminated through the spleen. Another problem was the foreign protein of the injected enzyme could lead to splenic failure!

More recent research [1] has investigated Dr. Kiesow's concept by introducing into the large intestine a non-toxic bacteria selected from the group that metabolizes hydrogen. As part of her work for the Office of Naval Research (ONR), Susan Kayar performed studies on deep-diving hydrogen-breathing pigs that had been fed the hydrogen-metabolizing bacteria [2, 3]. During the dive, the bacteria multiplied and fed on the gas mixture used in the dive by metabolizing the diluent gas released into the large intestine. The new product was simply vented from the large intestine. The metabolism of the hydrogen caused a reduction in the partial pressure of the metabolized gas in the large intestine, thereby increasing the diffusion of the metabolized gas from the blood and surrounding tissues into the intestine. To deliver the bacteria to the pig's intestines, Kayar simply packaged it in an enteric coating for oral ingestion. The coating was necessary to protect the bacteria while passing through the stomach. By the time the package reached the large intestine, it had dissolved and released the bacteria.

Since Kayar's invention [4] has the potential to revolutionize saturation diving, it is worthwhile examining some of the principles that underlie the process. The first step was to find bacteria capable of metabolizing hydrogen into methane but, naturally, the bacteria could not be toxic to the diver. Fortunately, Kayar found several bacteria that met the requirements for bacterial decompression, one of which was *Methanobrevibacter smithii*. The next challenge was to ensure the bacteria were capable of returning to the active metabolism. One of the preferred solutions was to wrap the bacteria in a slow-release capsule as a freeze-dried product. The intention was the diver would simply swallow one or more capsules containing the bacteria. The packaging would pass through the stomach and small intestine unharmed. Once in the small intestine, the capsule would begin to dissolve and would be fully hydrated and operational by the time it reached the large intestine, allowing the bacteria to colonize there indefinitely. To provide sufficient lead time for the bacteria to reach and colonize the large intestine, the diver would be required to ingest the capsule about 12 hr before the bacteria were needed to assist in decompression.

Conceptually, Kayar's invention offered the possibility of dramatically reducing decompression time. But it had not been tested. One of the first studies placed hydrogen-metabolizing bacteria inside the large intestines of rats (Panel 2.3). Sure enough, the hydrogen-metabolizing bacteria did indeed eliminate hydrogen dissolved in the rat's tissues and the rat's risk of DCS was subsequently lower.

How did the bacteria do this? The culture of bacteria that was introduced into the large intestines of the lab rats possessed an enzyme of the class known as hydrogenase, which is a protein enzyme that catalyzes the metabolism of hydrogen.

Panel 2.3. Hydrogen-breathing lab rats

To test the viability of hydrogen-metabolizing bacteria as a means of reducing decompression, live cultures of *Methanobrevibacter smithii* in a bicarbonate buffer were surgically injected into the proximal end of the large intestines of five rats via a cannula. The rats were placed in a box inside a dive chamber that was specially designed for operating with gas mixtures of hydrogen and oxygen and exposed to 100 m of sea water equivalent pressure of a hydrogen–oxygen mixture.

A stream of gas passing through the box was sampled by gas chromatography. The animals were then placed in a dry hyperbaric chamber specially designed for compression with mixtures of hydrogen and oxygen. As the rats breathed hydrogen, some of the gas was metabolized by the microbes in the intestines while the chamber gases were monitored by gas chromatography. The rate at which the rats released methane was measured by following the rate of hydrogen removal by the microbes. The study demonstrated that the rats that received the microbial treatments had a significantly lower incidence of DCS compared to untreated animals, and also compared to surgical control rats that received intestinal injections of saline. In fact, the *Methanobrevibacter smithii* cut the incidence of DCS by half.

The category of hydrogenase chosen for the biochemical decompression study was the methanogen, a hydrogenase that metabolizes hydrogen to form methane. Of the methanogens studied, *Methanobrevibacter smithii* was an ideal candidate for the purposes of biochemical decompression because this species is a common resident of the normal human gut flora and has no known pathogenicity. During its action, *Methanobrevibacter smithii* converts hydrogen and carbon dioxide to methane and water, consuming four hydrogen molecules for each molecule of methane produced. Under normal circumstances, the source of hydrogen for this reaction is the end-product of fermentation by other bacteria in the intestine. While most people on a Western diet usually harbor only small populations of *Methanobrevibacter smithii* and produce milliliter volumes of methane per day, there are some healthy individuals who produce up to 4 l of methane per day, thus metabolizing 16 l of hydrogen! The methane passes harmlessly from the rectum.

Calculating the amount of bacteria can be estimated by factoring in the length of activity, the volume of hydrogen to be consumed, and the length of time by which the decompression time is to be reduced. To determine how much bacteria the diver must ingest requires certain assumptions. First, it is assumed that the partial pressure of gas in the blood stream is supersaturated as the diver decompresses and no additional gas will dissolve into the blood stream. Second, it is known that the total volume of hydrogen in a diver per unit body mass is a linear function of the partial pressure of hydrogen to which the diver is exposed. Therefore, if a diver is at maximal depth and in a steady state, saturated with hydrogen, and sufficient bacteria were present to consume 50% of the body burden of hydrogen over the same time interval at which 50% of their body burden of hydrogen would normally be offloaded by traditional decompression procedures, the overall speed of decompression would be doubled, and the time to decompress would be halved. Of course, if a diver wanted to cut even more off his/her decompression time, he/she could be supplemented with greater quantities of bacteria, to remove even more hydrogen per unit time. Popping a few capsules containing bacteria certainly beats hanging onto a decompression line breathing mixed gas for hours at a time!

Kayar's research represents a fundamentally different approach to reducing DCS risk. Whereas previous research has sought to adjust dive duration and depth combinations, Kayar's work seeks to reduce DCS risk by actively eliminating a critical portion of the body's inert gas load. It is a radical approach, but research to date indicates that if divers are provided with the biochemical machinery to metabolize hydrogen saturated in their tissues, a significant reduction in DCS may be achieved.

Only a few years ago, a discussion of non-commercial divers using mixed-gas equipment would have been more than a little far-fetched to many diving professionals, and to suggest that safely engineered CCRs could be available off the shelf would have caused many to choke on their regulators. Similarly, if you had explained to the average technical diver a couple of decades ago that it would be possible to pop a pill that would halve their decompression time, you would probably have received some strange looks. Nevertheless, here we are in 2010, with technological innovations that herald the future of technical and SAT diving. However, while CCRs probably represent the future of scuba and while biochemical decompression may well reduce the risk of DCS, even with these advances, humans will still be restricted to depths in the 100–200-m range and they will still be required to undergo at least some decompression. The average depth of the ocean, however, is 3,790 m, which means using the most advanced SAT systems and most cutting-edge diving equipment, humans will still be limited to barely scratching the surface of the planet's least explored region. To embark upon real underwater adventure requires a more robust diving system and it is this that is the subject of the next chapter.

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Ocean Outpost
The Future of Humans Living Underwater
Seedhouse, E.
2011, XIV, 187 p. 56 illus., 51 illus. in color., Softcover
ISBN: 978-1-4419-6356-7