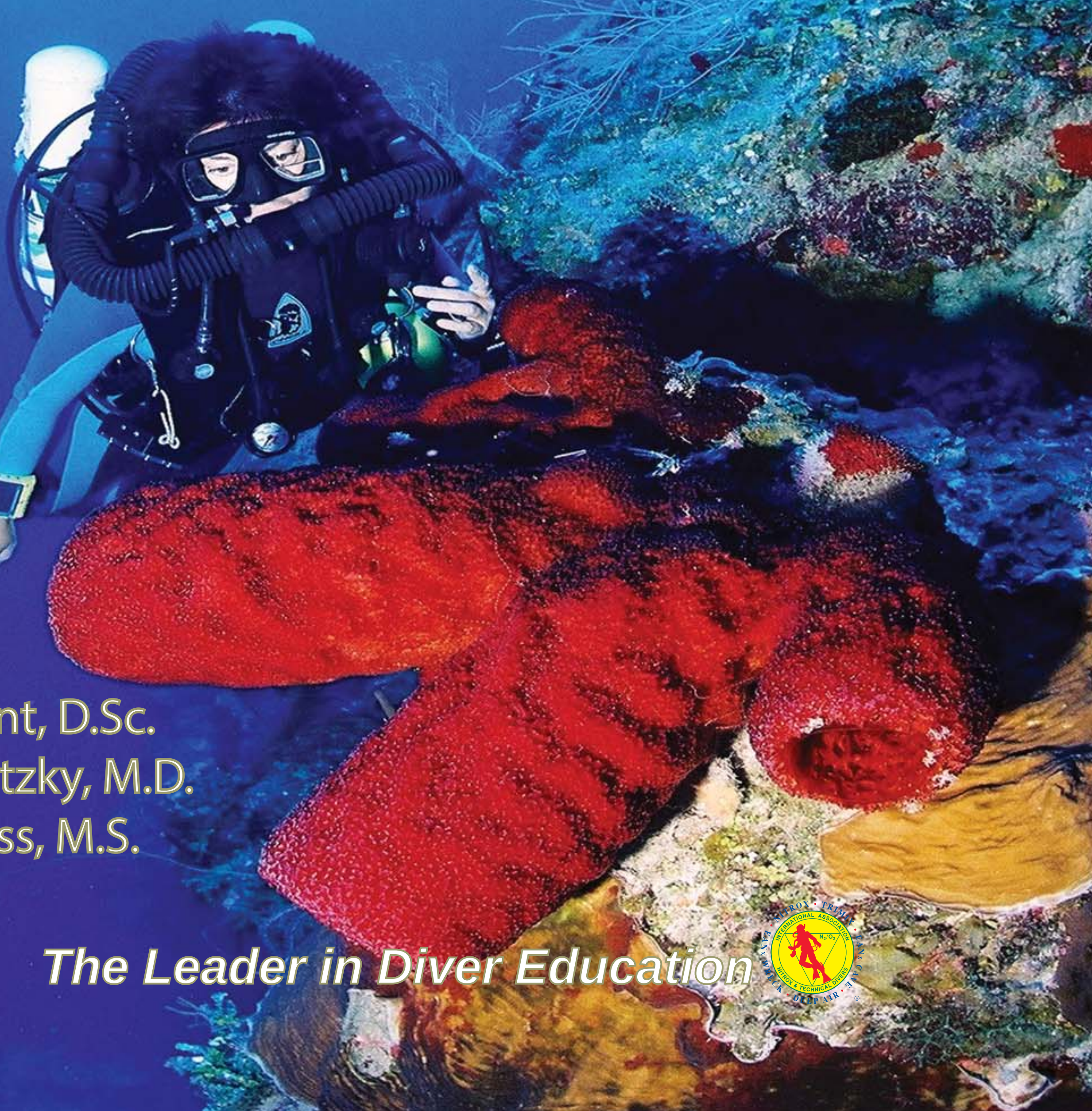
Tek Closed Circuit Rebreather

* CCR Technical Diving * Normoxic Trimix * Cave * Wreck *

The Adventure Begins!



Tom Mount, D.Sc.
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Joerg Hess, M.S.

The Leader in Diver Education

DISCLAIMER
Tek CCR

Neither the author nor the Board of Directors, Board of Advisors, or any other party associated with the International Association of Nitrox Divers, Inc. will accept responsibility for accidents or injuries resulting from the use of materials contained herein or the activity of SCUBA diving utilizing open, closed and/or semi-closed circuit equipment or breathing compressed air or alternative breathing mixtures, including combinations of Oxygen, Nitrogen and/or Helium and/or Neon.

SCUBA diving, including the use of compressed air and any gas mixture underwater, is an activity that has inherent risks. An individual may experience injury that can result in disability or death. Variations in individual physiology and medical fitness can lead to serious injury or death even with adherence to accepted standards of performance, specified oxygen limits, and the correct use of dive tables and computers. All persons who wish to engage in SCUBA diving must receive instruction from a certified instructor and complete nationally recognized requirements in order to be certified as a SCUBA Diver. The use of alternative breathing mixtures, such as combinations of Oxygen, Nitrogen and/or Helium and/or Neon, requires additional instruction beyond that offered in traditional SCUBA diving courses.

Trained and certified Scuba Divers, using compressed air or alternative breathing mixtures as described, are informed of the risks associated with SCUBA diving, and utilizing alternative breathing mixtures as described and ultimately bear responsibility for their own actions. Persons must not engage in SCUBA diving, and the use of compressed air or alternative breathing mixtures as described, if they are unwilling to complete a course of instruction, pass certifying examinations and evaluations, maintain their skill knowledge through active participation in diving activities, and accept responsibility for any injury or death that may occur when participating in SCUBA diving activities.

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Chapter 1 - Dive Planning

by Tom Mount, D.Sc., Ph.D.

Dive planning is the process by which divers determine and clarify the objectives of a proposed dive, rehearse the specifics of the dive plan, and review their proposed actions in order to eliminate or minimize the associated risks. To accomplish these goals, four important processes must occur: information gathering, group planning, personal planning, and contingency planning for personal and environmental unknowns.

Information gathering, the first step in the planning process, should include all the facts necessary to prepare a safe plan of action on the dive, and should recognize the variables and unexpected contingencies that might occur. In technical diving, detailed information gathering is paramount to the safety and survival of the diver and/or dive team.

When gathering information on a given location, you should refer to all available resources to ensure that both an adequate amount of information is obtained, and that the information is accurate and current. The basic references should include visits to the site, conversations with those who dive the site and printed reference materials such as cave maps or ship's blueprints.

Photo by Jim Kozmik

Once this preliminary information is gathered, a basic dive plan can be formulated. If there are charts or maps of the location, carefully review them and ensure that each person on the dive team is familiar with the specifics of the location. Discuss the impact your dive plan will have on the underwater environment. Also plan the route, duration and proposed actions of the dive.

Next, determine the equipment needed to perform the dive safely, along with any additional specialty equipment that will enhance dive performance. Then determine the correct gas mixtures to make the dive and efficiently decompress.

When beach diving, divers should determine wave patterns, probability of rip currents or long shore currents, underwater topography and location of safe entrance and exit points. On cave dives, teams should anticipate the entrance and underwater conditions, including surface hazards, current, silting, passage size, expected depth, and so forth. If there are reversing currents, the team should establish an optimum dive window.

When boat diving, investigate the particulars of water entries and exits from the craft. If the dive will be a fixed anchor dive, be certain you make visual reference and know where the anchor (upline) is located. If using decompression stages, do not affix them to the anchor line. The line may break free and the dive team could thus lose access to their deco gases.

If completing stops while drifting, determine the proper procedure for performing this operation. There are numerous methods of securing drift decompression and ascent lines, so insist on having the system explained anytime you are diving with a new operator, location or under different circumstances than those you are familiar with. When doing drift dives, be responsible and become informed. Do not assume anything. Be informed and be safe. All divers in the group on open water dives must have a lift bag. If they become separated, they will have a stable up-line and a location indicator for the diving vessel.

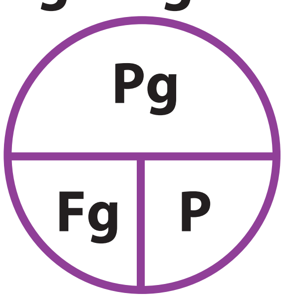
Each diver in the group needs adequate equipment and appropriate redundancy for a safe team dive. Prior to entering the water, perform a safety drill (known as an S drill). During this process, each diver will check their buddy's equipment for functionality and possible leaks. This includes breathing from the long hose, checking lights, and looking for any gas leaks in the tanks, valves and regulators. In cave and shore-based diving, the S drill is to be performed in the water. Even when boat diving, make a leak check upon entry into the water if conditions allow.

Gas mix planning is a major concern for technical divers. Determine oxygen management, narcosis planning, gas density considerations and decompression planning. In general, the longer the dive or the deeper the dive, the more detailed the dive plan must be. When making repetitive dives, make allowances for tracking residual oxygen in the system.

When planning CCR dives two of the greatest hazards are central nervous system (CNS) oxygen toxicity and hypoxia. Carefully plan out the combined risk of the planned PO_2 plus bottom mix gases for both diluent and bailout. In most CCR technical diving situations, an oxygen partial pressure (PO_2) of 1.3 ATA is the maximum target operating depth (TOD). When diving on a SCR, it can be as high as 1.4 ATA. For decompression the maximum PO_2 is 1.4 ATA on CCR, with 1.6 ATA being the recommended limit for SCR or OC.

In addition to CNS exposure, a diver needs to track the accumulation of oxygen tolerance units (OTUs), which effect whole body/pulmonary exposure. The OTUs are primarily a concern in saturation diving or when a need for treatment presents itself. As a rule, if a diver remains within a CNS exposure not exceeding 100% of the allotted dosage, OTUs remain within safe limits. On extended dive programs involving six or more continuous days of diving, the OTU limits may become the controlling factor in oxygen management. When planning partial pressures for the dive, first determine the PO_2.

$$Pg = Fg \times P$$



$$Fg = \frac{Pg}{P} \qquad P = \frac{Pg}{Fg}$$

EXAMPLE:

Assume the dive is to 160 fsw (48 msw) and the planned PO_2 is 1.3 ATA. The END is 100 fsw (30 msw). The diluent will have a PO_2 of 1.0 ATA.

Or, use IANTD Waterproof Tables C-3201B or C-3700 when looking for a desired PO_2.

Imperial $$Fg = \frac{1.0}{(160 \div 33) + 1} = \mathbf{0.17 \text{ or } 17\%}$$

Metric $$Fg = \frac{1.0}{(48 \div 10) + 1} = \mathbf{0.1724 \text{ or } 17\%}$$

Next, plan the END. Refer to the EAD formula:

Imperial

$$EAD = \left[\frac{FN_2(.74)\, x\, \text{depth} + 33(140 + 33)}{.79}\right] - 33 = 129.05 \text{ feet}$$

Metric

$$EAD = \left[\frac{FN_2(.74)\, x\, \text{depth} + 10(42 + 10)}{.79}\right] - 10 = 38.7 \text{meters}$$

Thus, find the desired END of 100 fsw (30 msw) for this dive:

Imperial $$END = \left[\frac{\text{targetEND} + 33\, x\, 0.79}{\textbf{\textit{depth}} + 33}\right]$$

Metric $$END = \left[\frac{\text{targetEND} + 10\, x\, 0.79}{\textbf{\textit{depth}} + 10}\right]$$

The equivalent FO_2 based on a PO_2 of 1.3 is 22% at a depth of 160 fsw (48 msw):

Imperial

$$END = \left[\frac{100 + 33\, x\, 0.79}{160 + 33}\right] = 0.54 \text{ or } 54\ \% \text{ Nitrogen}$$

Metric

$$END = \left[\frac{30 + 10\, x\, 0.79}{48 + 10}\right] = 0.54 \text{ or } 54\ \% \text{ Nitrogen}$$

ANSWER:

He = 100 –54 N –17 O_2 = 29% He

Thus, the mix will contain 29% He although the actual oxygen in the diluent will only be 17% based on a 1.0 diluent PO_2.

You could also use the IANTD Waterproof END Table C-3706 for 1.3 PO_2 at 160 fsw (48 msw). To determine the exact mix, go down the chart to 160 fsw (48 msw), then across until you are below the 100 fsw (30 msw) END. Note the Helium concentration. This is a mix of 22/23 on the chart.

For bailout an END of 120 fsw (36 msw) will be used, and a bailout PO_2 of 1.4 will be needed for a dive that is in an overhead environment (in OW a bailout PO_2 of 1.6 could be used).

Referring to the various IANTD Waterproof Tables available from your Instructor please note that on Table C-3706, if we go to 160 at a PO_2 of 1.4 we discover the FO_2 is 24% and the helium content for an END of 120 fsw (36 msw) is 13%. Thus the bailout mix will be 24 / 13. Obviously, this could also be worked out with the END formula.

To avoid mistakes in calculating PO_2, use the IANTD PO_2 Table C-3201B. You may also use the IANTD END Table C-3706 for PO_2 of 1.3 and 1.4. In addition, Table C-3201 can be used for tracking CNS% and OTUs. When they are combined with C-3201B the residual CNS% and PO_2 can be calculated as well.

Dive Example:

A wreck dive is planned to a depth of 200 fsw (60 meters). The dive will use PO_2 1.3 ATA. The bailout PO_2 cannot exceed 1.4 ATA. On both the diluent and the bailout cylinder the desired END is 90 fsw (27 msw)

Part Two:

The dive will have a bottom time of 40 min. For decompression, the PO_2 will be maintained at 1.4 from 40 fsw (12 msw) ATA, up through the 15 fsw (4.5 msw) stop.

Imperial

$$\text{END} = \left[\frac{90 + 33 \, x \, 0.79}{200 + 33}\right] = 0.417 \text{ or } 42\% \text{ Nitrogen}$$

Metric

$$\text{END} = \left[\frac{27 + 10 \, x \, 0.79}{60 + 10}\right] = 0.417 \text{ or } 42\% \text{ Nitrogen}$$

To provide accurate CNS and OTU calculations, use the IANTD OTU-CNS exposure planning tables and charts referenced earlier.

Now, put all the tables we've mentioned to use as part of this dive plan.

By referring to the IANTD PO_2 Table C-3201B, we find a diluent PO_2 of 1.0 requires a FO_2 of 0.14 (14%). Using the END equation the Helium content will be:

ANSWER:

He = 100 - 14 - 42 = 44% and the diluent mix is 14/44

Plan the bailout mix by referring to the IANTD END Table. You will discover at 200 fsw (60 msw) a mix of 20 / 38 will provide a bailout with a PO_2 of 1.4 and an END of 90 fsw (27 msw).

Plan the bailout gas needed by each diver as if this is a team of three divers. Base the calculation on the diver who has the highest RMV. In this case the diver with the highest RMV breathes at a rate of 0.7 cubic feet/min (20 L/min). Also assume a bailout EAN 70 cylinder is at 40 fsw (12 msw).

Compute the gas needed based on the diver breathing 0.7 ft^3 (20 L). Multiply times 1.5 and divide this number by 3.

Note that the diver, by himself, would need 19.6 ft^3 (555 L) to bailout and ascend to the first stop at 140 fsw (42 msw). This value was calculated based on the max depth gas consumption. Allow for stress at the time of the emergency and during deco up to the staged deco gas at 40 fsw (12 msw), including the ascent from 200 fsw (60 msw) a total of 66.11 ft^3 of gas (1872 L). Thus, the team would need to carry 66.11 times 1.5, or a total of 99.16 ft^3 (1872 L x 1.5 = 2808) L) of gas. For safety, round off to 100 ft^3 (2832 L) divided by 3 = 33.3 ft^3 (divided by 3 = 944) of gas per diver.

For planning, each diver would carry a 40 ft^3 (6 L) cylinder. The bailout EAN 70 deco gas needs will require another 114 ft^3 times 1.5 = 171.16 ft^3 (3231 L *x* 1.5 = 4847 L) To be staged or carried by the team if broken into individual team member responsibilities,

Notes:

each member would have to stage 57 ft^3 (1614 L) of EAN 70. In this case, each member could stage a 60 ft^3 (8 or 10 L) cylinder or the combined team could stage these cylinders on the deco line or from the boat.

Runtime Variation Planning

On a runtime table if you are using a 50-minute schedule but leave the bottom at 48 minutes, it is safe to subtract 2 minutes from each of the runtime depths. In other words if your first stop says 56 minutes, leave at 54 minutes. This keeps the actual stop duration the same, as it would be on the 50-minute schedule.

If you leave the bottom late then you must go to the next greater schedule and subtract the time differences, just as you did in the above example. If the ascent rate is faster than the schedule, stop 10 feet (3 meters) below the first scheduled stop for the time difference. If the ascent is slow but within 2 minutes of schedule then add the time to the runtimes at the stops. If the ascent is delayed more than 2 minutes, switch to the next greater schedule.

Photo by Wes Skiles

Dive 1:

Use IANTD/IAND, Inc. VPM B Constant PO_2 Dive Table (see page 10, Table A). A repetitive dive is planned for two hours later to the same depth again for a 30-minute bottom time.

Dive 2:

Use IANTD/IAND, Inc. VPM B Constant PO_2 Dive Table - repetitive dive (see page 11, Table B). Add travel time to first deco stop into bottom time and use the 2 + 2 Rule for CNS and OTU calculations.

Personal Planning

Personal planning is the most important part of the dive plan. It is the individual and his/her perception and interpretation of the planned dive that yields an acceptable or unacceptable performance. There are many aspects involved in personal planning, and the key is being comfortable with one's role in the accomplishment of the dive. In this area, we will be discussing the key components of a personal plan.

Risk analysis, acceptance and management are the major portions of a personal dive plan. This should begin with an introspective look into oneself to determine how one truly feels about the dive. During this phase, basic questions should be raised and answered honestly.

Review all aspects of your personal dive plan. As part of the risk analysis, review histories of similar dives. Determine if threatening situations and accidents have occurred, and if they have analyze what caused those events.

Once the cause has been discovered, develop a reaction response to compensate for the recurrence of a similar situation. List all the possible things that could affect dive safety and develop a response action to these possibilities. Decide if each risk to be encountered is worth the benefit of performing the dive. Prior to the dive, physically and mentally complete a checklist.

Personal comfort must be taken into consideration. While it is true that unfamiliar situations may lead to an expansion of personal capabilities, for safety's sake, a diver should not be pushed too far from his present comfort level. Anxiety from overextending the comfort level of a dive may cloud good judgment. If a diver is forced to function outside his personal comfort level, anxiety will add to the stress and overall risk potential of the dive.

If you are in the process of expanding your comfort level, do it in small and personally acceptable increments. Do not depend on someone else to maintain your safety or establish your limits. Even with the best of intentions, other divers cannot enter your mind and evaluate your mental capabilities for a dive. Dive buddies are limited to watching your performance and your verbal and body language communication for interpreting your comfort level. Remember the three basic ingredients that ultimately evaluate your survival and comfort potential. These are: Only you can swim for you. Only you can breathe for you. Only you can think for you.

Any time you have the slightest doubt in your ability to do any of these three, slow your progression toward more involved dives. A skilled buddy may be able to assist you for a short time if a swimming problem exists, but they cannot maintain that function indefinitely. No one can think or breathe for you, so avoid situations that cast doubt on your ability to complete the dive.

"Only you can swim for you. Only you can breathe for you. And, only you can think for you!"

An additional factor that determines a diver's personal comfort level is the combined mental and physical fitness that you maintain. A degree of physical fitness is needed to manage the equipment on land, and fitness is needed for propulsion skills.

Perhaps one of the most important aspects of fitness, however, does not become apparent until the diver is faced with adverse conditions. In this type of situation, watermanship and fitness may be the determining factors in survival. Even with superb physical fitness, a diver must also develop confidence and discipline combined with the ability to maintain mental focus. The mental fitness of a diver will be the determining factor in development of these attributes. Be sure you remain within both your physical and mental conditioning.

Individual "what if" scenarios are in addition to the team plan, but they should also be addressed before the final dive plan is agreed upon. These must be placed in the risk analysis table when deciding how to most efficiently deal with them. Exploration of the "what if" scenario includes both the environmental factors and risks associated with equipment dependency.

Listed below are sample "what ifs" that may be encountered. Analyzing the individual risk associated with a dive can expand these reasons. List these on a separate piece of paper.

1. What if... I get lost? Determine a means of finding your way out or in being located by a surface crew/boat. The exact solution will depend on the type of dive, the location, and the community standard for locating lost divers.

2. What if... I lose a bailout stage cylinder? Abort the dive and begin an ascent to the surface.

3. What if… I lose all the gas from my diluent cylinder? Plug the stage cylinder into the manual diluent addition valve and use it. For buoyancy control manually inflate the BC as required.

4. Think and continue this list until you have developed at least 10 or more personal "what if" scenarios.

Once your personal "what ifs" are listed, determine the solution to each situation and visualize a method for overcoming them. Once you have identified the problem, developed the solution, and visualized its accomplishment, do not dwell on it. You have achieved the goal of overcoming this specific problem. Dwelling on problems has two negative effects. First, you begin to worry about it. Worry creates stress and may lead to apprehension and result in either an incident or a dive that you do not enjoy. Secondly, by continuing to think about the problem, with so much emphasis on the problem, the mind may in fact create the circumstance.

Am I confident in my ability to manage rebreather specific emergencies? This is the most important

Notes:

Table A

Dive 1 Using IANTD / IAND, Inc. VPM-B Constant Partial Pressure Dive Tables

Mix 14 / 44 1.3 PO2 and 1.4 PO2 for Deco - 200 Foot / 60 Meter Dive 30 Minutes BT

FSW MSW	MIX	ATA	END	TIME	Set point	%CNS	OTU	18 / 38 Team deep bailout 64.76 x 1.5 cubic = 97.14 total) 2076.5 L total x 1.5 =3114.76 in 3 person team 25 ft^3 each 30 ft^3 stage 1038.2 L (5 L) stage for bailout use 19 40 and the OC 19 40 table
200 60	14 44	7.06	85 26	30 CCR BO	1.3			10.48 ft^3 367.5 L used on ascent to first stop
190 57		6.76						
180 54		6.45						
170 51		6.15						
160 48		5.85						
150 45		5.55						
140 42		5.24						
130 39		4.94		33 33 (1) (1)				3.5 123
120 36		4.64		34 34 (1) (1)				3.2 115
110 33		4.33		35 35 (1) (1)				3.0 108
100 30		4.03		36 36 (1) (1)				2.8 100
90 27		3.73		37 38 (1) (2)				5.2 186
80 24		3.42		39 41 (2) (3)				7.2 255
70 21		3.12		41 44 (2) (3)				6.6 234
60 18		2.82		44 50 (3) (6)				12 210
50 15		2.52		48 56 (4) (6)				10.8 378
40 12		2.21		53 61 (5) (5)	1.4 E 70			EAN 70 / 42.8 x 1.5 = 64.2 ft^3 1566 L x 1.5 = 2349 Total 32.1 ft ea.(40 stage) 1174 L (5 L stage) each 7.5 275
30 9		1.91		59 67 (6) (6)				7.8 288
20 6		1.61		62 71 (3) (5)				5.5 200
15 4.5		1.45		80 95 (20) (22)		47%	39%	22.0 803
Total				80 93		47%	39%	

Table B

Dive 2 Using IANTD/IAND, Inc. VPM-B Constant Partial Pressure Dive Tables

Same mix 2 hour SI – 200 Foot / 60 Meter Dive 30 Minutes BT

FSW MSW	MIX	ATA	END	TIME	PO_2	%CNS	OTU	NEEDED
200 60	14 44	7.0	85 26	30	1.3			18 / 38 Team deep bailout 66.78 x 1.5 cubic = 100.17 total in 3 person team 33.39 ft^3 each 40 stage) 2355.5 L total x 1.5 =3533.25 or 1177.5 L each (6 L) stage for bailout use 19 40 and the OC 19 40 table
190 57		6.7						10.48 ft^3 367.5 L used on ascent to first stop
180 54		6.4						
170 51		6.1						
160 48		5.8						
150 45		5.5						
140 42		5.2						
130 39		4.9		33 33 (1) (1)				3.5 123
120 36		4.6		34 34 (1) (1)				3.2 115
110 33		4.3		35 35 (1) (1)				3.0 108
100 30		4.0		36 37 (1) (2)				2.8 100
90 27		3.7		37 38 (1) (1)				5.2 186
80 24		3.4		39 41 (2) (3)				7.2 255
70 21		3.1		41 45 (2) (4)				8.8 312
60 18		2.8		44 50 (3) (5)				10.0 350
50 15		2.5		48 57 (4) (7)				12.6 441
40 12		2.2		53 62 (5) (5)	1.4 E 70			EAN 70 62.6 x 1.5 = 93.9 ft^3 2288.4 x 1.5 = 3432.6 L total 31.3 ft^3 (1144.2 L) each stage 40 ft^3 (5 L) stage 7.6 275
30 9		1.9		59 70 (6) (8)				10.4 384
20 6		1.6		63 76 (4) (6)				6.6 240
15 4.5		1.45		88 114 (25) (38)				38 1389.4
				88 114		75% 71%		

**Add travel time to first deco stop into bottom time and use 2 + 2 Rule for CNS and OTU calculations.

question to ask. Survival in an emergency requires a "yes" to this question. At this point, review and practice all emergency skills and responses taught in earlier levels of CCR training. Any oxygen or carbon dioxide problems will present themselves as confusion to the diver. This is one of the major (subtle and usually undetected) symptoms. Considering this, if at any point a diver feels uneasy, first switch to a known safe breathing gas (off board/stage/bailout rebreather) and take sanity breaths. It may require more than one sanity breath to relax, or in some instances you may discover it's not a rebreather related problem. Regardless, take the time to determine if there is or is not a problem that needs to be corrected.

Generally, the common reasons for taking corrective actions vary from feeling unusual to recognized symptoms and include the following steps:

1. Go to a known safe breathing medium and take sanity breaths as required. A sanity breath is the act of going to an OC gas or back-up rebreather system, with an acceptable PO_2 and END plus adequate capacity for the depth to be breathed at. The sanity breaths allow the diver to take one or more breaths as needed to evaluate any unusual feelings or symptoms they may be experiencing, as well as any suspected problems with the rebreather. Since the first symptom of hypoxia, hyperoxia, and hypercapnia is usually confusion, the sanity breath is a diver's safest reflex in these situations. Sanity breaths will allow clear thinking; enabling the diver to analyze the problem, determine if one even exists, solve the problem or take other corrective action. At the end of the sanity breaths, appropriate problem solving actions must be taken by the diver. In some cases you may have to do more than one sanity break to correct a given situation. Once the problem is corrected, return to the loop if a safe PO_2 is verified. In the event of a canister breakthrough or other uncontrolled hypercapnia events, remain on OC and terminate the dive.

Notes:

2. Check the PO_2 Flush as/if needed. For instance, if you have a PO_2 set point of 1.3 and it drops to 1.1, it is a good indication that the solenoid is not working and may have failed in the closed position. If the diluent PO_2 is 0.8, do not flush the unit. Flushing would drop the PO_2 more, and you would need to add more oxygen. On the other hand if the PO_2 was down to 0.4, you would flush the unit (especially if you have been so careless as to allow the PO_2 to drop to this level). It is most likely dropping in a state of momentum; therefore, it is possible that the inspired PO_2 is even less than the level indicated. If you question the accuracy of the displayed PO_2, flush the system to see if the indicated PO_2 and diluent PO_2 match.

If you have just made a rapid descent and notice the PO_2 is at 1.45 then monitor the display closely to ensure that the increase is due to spiking from the rapid descent (provided the PO_2 does not continue to increase) simply breathe down to 1.3 where you can dive the unit by either manual control or solenoid control. If the spiked PO_2 exceeds 1.6, flush the system to bring the PO_2 back down to less than 1.6. Then breathe it down to the set point to be maintained and keep it at this value. If the flush does not bring the PO_2 down before you need to breathe, then take a sanity break, return to the loop, and flush the system down to less than 1.6. When reacting to situations use common sense. Remember if the diluent PO_2 is too high you will not be able to flush the loop PO_2 down to an acceptable level.

3. If it is a PO_2 problem, take the appropriate action to manage the particular problem. For example: correcting a high PO_2 from either a failed solenoid or a leaking manual addition valve may require turning off the supply gas. Once the PO_2 is safe to breathe, manage the problem by going back on the loop and manually turning the oxygen supply valve off and on. At depth this requires barely cracking the valve and then turning it back off. Caution is required. Practice is critical. Only open the valve partially.

Each CCR requires developing a sense of timing in doing this process. Usually, if a diver waits to see the PO_2 increasing towards the desired upper range of the intended PO_2 they will discover that it overshoots that value. When manually controlling an open solenoid remember you must create a management range. For instance if the desired average is 1.2, allow the PO_2 to go up to 1.4 and then breathe the unit (with oxygen) down to 1.0. This will provide a fairly long interval between valve openings and give a stable, easy to manipulate condition.

A second method to control an open solenoid: once the oxygen supply gas is turned off and the PO_2 is at a safe level to breathe, switch to a staged oxygen cylinder or even a diluent with a higher PO_2 than the onboard diluent by connecting it to the manual addition valve. On low PO_2 it is actually a simpler management procedure, since you will monitor the PO_2 closely and manually add oxygen into the loop, maintain the planned PO_2. For divers who fly the CCR manually, or at minimum loop volume, this will be a normal style of diving.

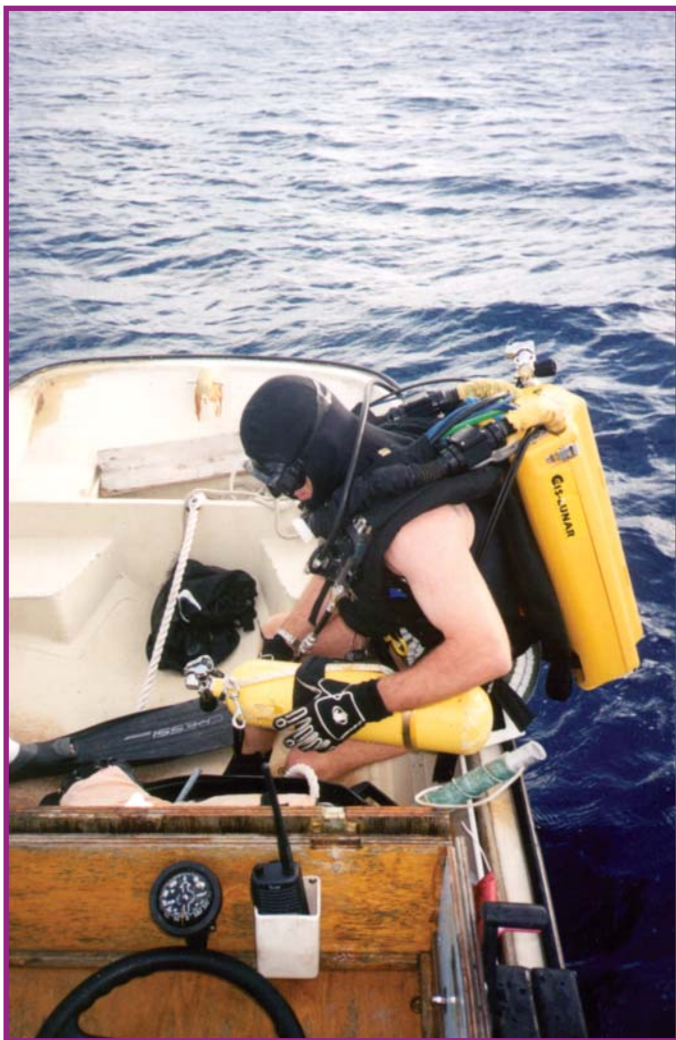


Photo Courtesy of Joseph Dituri

4. If you have ascertained that you have a canister breakthrough, it is imperative to bailout to OC. You must be able to problem solve by source management. This ability requires an in-depth understanding of failure points and of the unit as well. The things that lead to emergency situations on CCR all generate from a source. If the diver can identify the source of the problems, they can take a corrective action to manage it. In many cases going to the source of a problem may resolve it, and the unit may be "flown" in a normal method. In other situations the problem can be managed so the diver stays on the loop safely.

Source Identification

Oxygen problems - oxygen supply source: The first action following a sanity breath is to achieve a safe breathing gas and return to the loop. Use the techniques that you've been trained on and as discussed above.

The second step is to identify the cause of the failure, while still managing the problem from the source. High PO_2 may be caused by the solenoid failing in the open position; in this case the practical solution is to continue managing the problem by controlling the oxygen supply valve. Second alternatives are turning off the oxygen supply valve and connecting a secondary oxygen supply (or even diluent supply) that has an acceptable PO_2 to the manual oxygen addition connector, and then control the PO_2 manually. A third method is having an extra off-board connector so that either an additional diluent or oxygen supply may be connected into the system. This avoids the need for switching connected gases underwater.

What to do if you have a leak in an Schrader valve, LPI hose or other design feature of your particular CCR: If possible isolate the problem (i.e. disconnect the Schrader valve, LPI hose or other failed component of the CCR design), thus allowing the solenoid to control the set point.

Spiking: Flush the system down to a safe PO_2 level. This can only be accomplished with a diluent that is low enough to affect a drop in PO_2; it is recommended that the diluent PO_2 does not exceed 1.0 at depth.

Improper calibration of the unit: If you suspect the display PO_2 reading to be inaccurate, either go to SCR mode of operation or bailout on OC or a bailout rebreather. Abort the dive. Once on the surface recalibrate the unit. Low PO_2 may be caused by the solenoid failing in the closed position. In this case, the diver must dive the unit by manual oxygen addition. Of course, a safe breathing medium must be insured immediately.

Loss of oxygen supply gas: There are a couple of options for this problem. If an additional oxygen supply has been carried, the diver may connect this source into the manual addition of the CCR and fly the unit manually from the alternate oxygen source. Another option is dependent upon the bailout cylinder mixture. Most of the time divers will plan a bailout gas with a PO_2 between 1.4 and 1.6 at the maximum depth of the dive. In this case (assuming the diluent is a PO_2 of 1.0 or less) simply plug in the bailout cylinder to the manual addition and add the higher PO_2 bailout gas diluent to maintain a more acceptable breathing mixture. At some point it may become necessary to switch to SCR mode and again use the highest (safe) PO_2 gas available. As the diver ascends it is wise to flush the system more frequently. Eventually you may want to switch to OC or a bailout rebreather in order to keep the highest PO_2 for decompression purposes. An alternate means of control is to plug into a dive buddy's manual addition LPI hose and inject enough oxygen to bring the partial pressure up to 1.5 then disconnect. This gives you several minutes before it is breathed down to 1.0, at which time the procedure may be repeated. If the oxygen is depleted during the 20 fsw (6 msw) stop, either do as instructed above (2) and inject oxygen from your buddy's unit or take a breath of OC oxygen and exhale it into the unit.

Other causes of diminished PO_2 include:

1. Too rapid of an ascent
2. Oxygen supply valve turned off or out of O_2
3. Failure to activate the solenoid electronically

Photo by Tom Mount

4. On SCR
    a. Rapid ascent
    b. Over breathing
    c. Breathing the loop down once the gas is turned off or exhausted
    d. Improperly keyed passive SCR
    e. On some passive SCR inheritance due to over breathing
    f. Mistake in gas planning for the dive
    g. Diving active SCR beyond its design limitations

Diluent related problems - diluent is continually flowing into the loop: If the unit has a diluent "in-line" cutoff valve simply open and close it to control the addition of diluent into the system. If it does not have a cutoff valve then control the flow of diluent by opening and closing the diluent valve. If the system only features manual diluent addition and the Schrader valve or LPI hose is allowing diluent to leak into the system, you may address the problem by either disconnecting and reconnecting the diluent quick disconnect or by controlling the supply gas valve. Frequently, the valve on manual additions (this is true of both diluent and oxygen) will be stuck in the "on" position. Once the gas flow is under control the diver may be able to free the push valve and regain normal operation. Also, the Schrader valve or LPI hose may simply have debris in it. Disconnecting and shaking it some will clear this out and the diver may discover it works correctly once reconnected.

Diluent PO_2 is above the planned set point of the dive: In this case the diluent cannot be added into the system and the dive plan should be modified to a shallower dive. If an unplanned event caused the diver to descend below a level where the diluent is at an acceptable level, avoid using diluent as much as possible until you ascend to a safe depth. Preplanning dive gas mixtures easily avoids this problem. Always remember if the diluent PO_2 exceeds the planned set point limits, it should not be used on that dive. Also, if the diluent is very close to the set point it will make it more difficult to flush the loop down from a high PO_2 situation.

Bailout using onboard diluent: Using onboard diluent for bailout with an appropriate PO_2 is an acceptable practice in shallow water, however let's consider the safety of this in deeper water. If a diver

Notes:

breathes 0.7 ft^3 (21 L) a minute at the surface, and bails out on a 20 ft^3 (3 L) cylinder at 200 fsw (60 msw), then at depth they would be using 4.9 ft^3/min. Thus, the 20 ft^3 (3 L) cylinder even at full capacity will only last 4.08 minutes. It is apparent on deep dives that a diver should not use onboard diluent for bailout or for sanity breaths. You may wish to remove the onboard bailout system when diving deeper than 130 fsw (39 msw). **Many experienced deep CCR divers regard bailout to an onboard diluent supply as suicidal.** It is recommended that divers compute how long an onboard diluent will last at all depths to 200 fsw (60 msw). Then, decide on the safety/danger of this feature for deeper dives. **Be prepared to go to your off-board OC regulator for sanity breaths at any depth.**

Onboard bailout is free flowing through the bailout mouthpiece: Either block gas-flow to the mouthpiece if possible, or shut off the onboard diluent. If the onboard diluent is shut down, the diver may turn it off and on to satisfy diluent and buoyancy needs or shut off onboard diluent and use off-board diluent (provided the diluent is acceptable at the depth of the switch). With most CCR designs the onboard diluent may have to be turned on and off for buoyancy control. If you have another LPI inflator off the in-board gas then you may opt to switch to it.

Sensor related problems - Sensors are reading erratically: Switch to a set point that is lower then the diluent PO_2 and then flush with diluent. See if any sensors agree with the diluent flush. Often the sensors tend to settle down once they are flushed with dry gas. If the sensors disagree, keep the set point low and manually fly the unit based on the sensor(s) that agreed with the diluent flush.

Two sensors read identically while the third sensor reads high or low: Again, flush with diluent to determine if the two sensors are reading correctly. In most cases they will be. If the two sensors are correct, the CCR will operate normally based on its averaging circuits/voting logic. On the other hand, if the sensor reading out of range is the accurate one, go to a low set point and fly the unit manually and remain watchful.

All sensors are giving incorrect reading: If this occurs while swimming at a constant depth and the diver was employing minimum loop volume, the unit can be controlled by adding the oxygen they metabolize. In other words, when there is not quite enough gas volume inject a small amount of oxygen. Once depths are changed the diver will have to dive the unit in SCR mode or bailout to OC or a bailout rebreather.

Electronics problems - the primary display is lost: Abort the dive and dive the unit based on the secondary display. On most units this will require manually flying the CCR, using the secondary display to ensure the correct PO_2 is maintained. On some units, such as the Inspiration, the secondary display will automatically become the oxygen controller and can control the solenoid. However, it is recommended under these conditions that the diver control the unit manually so the power usage by the secondary display can be minimized.

Sensors do not read above 1.2, even if oxygen is added or the set point is at 1.3, and the depth is 160 fsw (48 msw): Suspect that the sensor voltage is low on all sensors and that they are not capable of reading above 1.2. Thus, the electronics cannot display the true PO_2. Flush the loop until the PO_2 is below the indicated 1.2. The sensors should read correctly if under the output value of the sensors. Abort the dive and fly the unit at 1.0 to ensure the sensor output will be correct. Alternatively, the diver may do SCR bailout and still monitor the PO_2 when it is below 1.2. At 20 fsw (6 msw) flush the unit with oxygen for decompression purposes. This is a rare event but has happened to at least two divers. If a diver can over-pressurize the system on the surface, they can prevent this problem by checking that the sensors can output enough to read high PO_2. Staggering the replacement of sensors helps. Frequent checking of sensor output voltage with a meter, or within the system as is possible on some units, will also help avoid false readings. Some manufacturers recommend changing all sensors at the same time. To be prudent do not dive sensors, whether they are staggered or changed at the same time, until failure.

All electronics are lost: If this occurs while swimming at a constant depth, maintain minimum loop volume and manually add oxygen as it is metabolized. The diver may continue the same technique until a depth change is required or ascent is commenced. Some may feel more comfortable diving the unit in SCR mode. Once a depth change is encountered, the unit must be dived in SCR mode. Alternatively, use a bailout rebreather or switch to OC bailout. In this situation at 20 fsw (6 msw) flush the system with oxygen for deco, if a bailout to OC has occurred go back on the loop and flush it with oxygen.

Loop integrity problems - the counterlung is

Notes:

filling with water: If the design permits it, loosen the counterlung dump valve and then flush the system while pressing the dump valve. Roll as needed to remove the water from the counterlung. Once the water is dumped remain alert for more water intrusion into the system and be prepared to repeat this sequence. By clearing the flooded counter lung there is a very low probability of having a totally flooded loop inclusive of the canister.

The counterlung is filling with water, and does not have a dump valve to eliminate the water egress into it: Check to see if the source/problem may be corrected. Swim with your feet slightly down to keep the water in the lower portion of the counterlung. If the problem continues it will eventually migrate into the canister. Be prepared to bailout to OC, or a bailout rebreather as the canister becomes flooded, or if breathing resistance becomes too great. It is recommended that divers add a dump valve or other water removal system to units that do not incorporate these. **A flood on a deep dive or in an overhead environment can be catastrophic.**

The loop is totally flooded and you are unable to breathe: First bailout to OC. If the system is flood recoverable, invert and shake water into counter lung(s). Roll, press manual diluent addition, and purge water from the dump valve. You must bailout to OC or a bailout rebreather if the system is not flood recoverable. In either situation terminate the dive.

The counterlung has been torn: This allows water to egress into the system. Try to pinch off the torn portion of counter lung to stop water entry and terminate the dive. Remain on the loop if possible.

Pinhole leak in counterlung: In this situation (as long as there is a slight pressure in the counterlung) very little water will leak into the counterlung. The diver may not have to take a corrective action. At the end of the dive, you must repair counter lung.

System has a torn exhalation hose: Pinch the hose together and blow water that has intruded into the counterlung. Terminate the dive. If the intrusion of water is beyond the CCR's ability to prevent a full loop flood, bailout to OC or a bailout rebreather.

System has torn inhalation hose: It is possible the diver may breathe water and the canister may flood. As a preliminary step, pinch hose shut and stay on loop unless the canister floods or there is too much water in the inhaled gas. In this case, you should bailout to OC or a bailout rebreather.

Canister problems - The diver becomes aware of symptoms of hypercapnia while exerting. First stop activity, switch to OC for sanity breaths, return to the loop, (diluent) flush the loop and see if symptoms persist. If no symptoms are present, terminate the dive and avoid exertion. If symptoms persist, you need to bailout to OC or a bailout rebreather and terminate the dive.

An acidic taste develops from the inspired gas: Suspect that water is in the canister, be aware that it is losing its ability to absorb CO_2, and that there is the probability of a caustic cocktail. If the diver elects to stay on the loop, avoid a head down posture. This will decrease the possibility of a caustic cocktail. You must also remain vigilant for hypercapnia problems and flush the system at regular intervals. At the first sign of a caustic cocktail (or any unusual feeling such a shortness of breath) you must bailout to OC or a bailout rebreather. The dive should be terminated at the first detection of this situation.

Symptoms of hypercapnia are noticed while swimming at an abnormal pace: The first step is to switch to OC for sanity breaths. Once stable, you may double check for symptoms. Go back on the loop and flush the system. Note how you feel at rest. If any unusual sensations exist, you need to bailout to OC or a bailout rebreather and terminate the dive.

Photo by Jim Kozmik

Notes:

The canister is on its second dive with the same absorbent and the diver just does not feel normal: In this case suspect that the canister was not sealed well between dives and the absorbent material is used up. Bailout to OC or a bailout rebreather and terminate the dive.

The diver suspects the canister has failed and has symptoms of hypercapnia (even after sanity breaths, the symptoms return): In this case the only safe solution is to make a switch to OC bailout or a bailout rebreather.

The canister is flooded: The diver must bailout to OC or a bailout rebreather unless it is a flood proof canister, in which case the appropriate flood recovery technique may be used.

Bailout gas problems: Ensure bailout system is rigged fully and correctly to provide low drag, ease of access, and is free from being dragged in silt, etc.

Leaking o-ring at connection point of first stage and valve: Turn gas off except while in use. If the gas is being actively used, turn on only when it is actually being breathed or add gas and then back off when inactive.

Second stage is flooding during OC bailout: In this case the non-return valve failed or there is a hole in the diaphragm. Gently press purge while inhaling and this will blow the water out.

Loss of bailout gas supply: Communicate to your buddy that you have lost the bailout system and the team must terminate the dive.

Bailout rebreather is flooded: Terminate dive and communicate the problem to the team members. The entire team must terminate the dive.

Bailout regulator OC is free flowing: Turn unit on while inhaling, and turn it off during exhalations.

Gas supply hose failure: If a gas hose fails turn off the regulator and use an alternate gas supply. If needed, switch regulators from another gas source.

In addition to correcting these problems, also ensure that if you're using a bailout rebreather it is functioning and pressure is maintained in the loop at all times to avoid flooding. If using a bailout rebreather, frequently check that it has a safe PO_2 and that the END of the diluent for bailout is acceptable. Check functionality of system periodically.

Pre-Dive Planning

Pre-dive set-up and pre-dive breathing/system check are crucial in avoiding problems with the rebreather and your support systems. Pre-dive checks will confirm that the system is set-up correctly and functioning safely.

Pre-dive set-up includes filling and analyzing cylinders and properly assembling the CCR. During the assembly process, inspect and lube O-rings as needed. Observe sealing surfaces for integrity and secure all attaching surfaces. Periodically check sensors for voltage output and response time. A slow responding sensor indicates the sensor is aging and may be marginal for diving.

The checklist below is a an example. You must also review manufacturer guidelines. Based on the specific protocols for your CCR unit, add steps to this list as needed.

1. Turn gases on, then off, and record pressure to determine if there is a leak somewhere in the gas systems.

2. Check that the inhalation, exhalation hoses, and their non-return valves are assembled correctly and functional.

3. Do a positive loop test. Allow at least 5 minutes to observe for any leaks.

4. Perform a negative loop test. Allow it to sit for a minimum of 5 minutes (on some systems the negative test should be longer per instructions).

5. Activate electronics (in some units the electronics are inside of the loop and need to be activated upon set up).

Pre-Dive Check: Correct any problems or developing issues identified on your last dive, before proceeding to the formal pre-dive check!

6. Check accuracy of all electronic displays and analog displays as relevant.

7. Check if the pressure in the oxygen and diluent supplies has decayed. If there is a leak, fix the leak before proceeding.

8. If applicable, ensure all gases and variables are correctly defined in the electronics and that manual and electronic readouts are consistent with each other.

9. Run a check on systems that have an onboard technique for checking sensor voltage and ensure all sensors are within acceptable range.

10. Calibrate system: If doing a manual calibration, flush the system totally for at least 3 cycles. Often 4 or more cycles are required to have a 100% oxygen environment in the loop. While at 100% oxygen (on systems that have the capability) check the sensor voltage to verify it agrees with the value for a partial pressure of 1.0.

11. When calibration is complete, observe the PO_2 readings. If they tend to drop off sharply, the calibration is most likely in error. In this instance, repeat calibration.

12. If the system does not have a two-point calibration you may want (not mandated) to flush with diluent (again three times) and check that the diluent PO_2 is accurate. This also will provide an indication of sensor linearity. Prior to doing this, check that the set point is below the partial pressure of the diluent, that the system is turned off, that it is in manual mode or that the oxygen is turned off and gas is vented from the oxygen supply line. If applicable, check sensor voltage for correct output.

13. Check remaining battery time and be sure it is adequate for the planned dive.

14. On systems that "go to sleep" on the surface, be sure to activate the electronics prior to breathing on the loop. At least one system has a "start dive" mode that must be activated prior to diving.

15. Ensure that all manual gas control valves or switches are set in their correct position and are functioning.

16. Verify all electronic gas control functions and any switches that may be applicable are in the correct position and operational.

17. Conduct an S drill on the system. Check completely for any leaks or system abnormalities. Check the bailout system to ensure it is functioning

Notes:

Photo by Tom Mount

properly. If you are using OC bailout, be sure there are no leaks, no free flows, etc. Check that the LPI hose and fitting will allow you to plug into the manual addition valve if the system is equipped with one. It is advisable to have an interchangeable low-pressure fitting on the counterlung, the BC and dry suit so the source gas may be switched in event of a failure. Check the manual addition valves for smooth and correct operation. Ensure the rigging of bailout systems allows them to be accessible and protected from damage. If a bailout rebreather is used, check its components in the same manner as the pre-dive check on the primary rebreather. If used, check lights and lift bags plus reels.

18. Pre-dive breathing: this process conditions the canister. Verify that the solenoid is firing and the displays are responding to the injection of oxygen. Check the set-point is correct and holding. Confirm that a safe breathing gas is in the loop. The pre-dive check should be performed on a low set point. During the pre-dive check also breathe from the bailout system, check BC inflation, and all systems needed for the dive.

19. The pre-dive breathing sequence should be a minimum of 2 minutes for warm water and 5 minutes for cold water. **Note: If a bailout rebreather is used, follow the same procedures on it!**

20. Immediately prior to entering the water verify that the unit is on, that there is a safe breathing mixture, that the automatic diluent addition valve (ADV) (if applicable) works and that any and all manual addition valves respond. Start the dive at the proper set point.

21. At depth, verify a change to the desired set point and that the solenoid still works. Even if controlling the system manually, you should still verify the solenoid fires provided the system uses a solenoid. Some CCRs, like the KISS model, may not use a solenoid as a standard component on the system.

On every third or fourth dive, at 20 fsw (6 msw), flush the system with oxygen and verify if it will obtain a PO_2 above 1.55. This will verify the voltage and response of the sensors. This is important. As sensors age, they may have adequate voltage to calibrate at 1.0 but may not be capable of indicating values above 1.2. If this happens a diver may read a display of 1.2 and actually have 2.0 in the loop. The occasional oxygen flush at 20 fsw (6 msw) will alert the diver to any possibility that the sensor output is not adequate to read above 1.0.

Responsibility: Evaluate both your physical and mental conditioning. Determine if you have what it takes to do this dive. This evaluation must be honest. Don't undertake a dive out of false bravado. Know in your heart that you can deliver a 100% effort. Be certain the team can depend on you. The importance of both physical and mental conditioning cannot be overemphasized in technical diving. If you are going to participate, accept and pay the price of staying in good physical and mental condition. Understand in your own mind that you will not be a person that is dependent upon the other team members. Technical diving is a hostile environment for dependent divers.

Another important aspect of responsible dive planning involves awareness. Are you absolutely aware of the dive's objectives and the technical components of the dive? While a level of trust is needed for every dive, there is a big difference between trust and a "trust me" attitude. The "trust me" leader expects you to put your life in their hands and follow them wherever they decide to go. Never, ever get yourself in this position.

If a dive is completely or partially exploratory, this fact needs to be established at the outset. If one member of the team is elected as the leader, their role must be defined. Responsibilities must be established. Conditions for dive termination must be fully defined. And, never forget one simple rule: ***Always trust in yourself and your personal survivability.***

When planning a dive, it's easy to get wrapped up in the technicalities and overlook the reasons why you're doing the dive in the first place. Anticipate the fun you're going to have. Visualize what you may see. Imagine how the members of your dive team will react to these aesthetic elements. As part of this exercise, develop an understanding that you are both a team member and a solo diver. Estimate the abilities of others in your dive team, but always mentally prepare yourself as if you are diving solo. This approach virtually guarantees that you will not exceed your personal limits and expose yourself to extraordinary risks. Besides, if you become separated or find yourself faced with a life-threatening event, you will most certainly face the situation alone. Remember, only you can think, breathe and swim for you! Plan dives within your personal limits and self-rescue abilities. It is also crucial that you remain within your abilities to assist or rescue a dive buddy. As a team member you are responsible to the other divers. In return, ascertain that each member is capable of rendering help to you.

Personal gas management: In this planning stage, the diver will become aware of their oxygen metabolism rate, amount of diluent gas to be used, their Surface Air Consumption (SAC) rate for OC bailout needs and the amount of gas in psig/bar they use when switching tanks. First, one must determine the SAC rate at a moderate swim pace. This can then be used as the normal swim rate SAC. To do this, swim at a predetermined constant depth for a period of at least 20 minutes. It is recommended that this be performed when a tank is between 1/2 and 2/3 of its rated pressure. In addition, this provides a more realistic value if done once the diver has been in the water diving or doing skills for long enough duration to add some degree of fatigue.

IANTD Tables are available to convert SAC to RMV values. Locate the proper table and find the tank size from which you were breathing. Go down the column until you reach the single tank consumption rate. This will give you RMV values for gas planning.

Notes:

Should you decide to switch to a different tank size simply match the new tank volume to the RMV value. Next look at the left side of the page. Note the psig/bar per minute value on the new cylinder. Remember to convert to double tank values if applicable.

Group Planning

Group planning is the process used by the overall dive team to determine understanding and acceptance of the objectives of the dive and the responsibilities of each diver. The specific items addressed include but should not be limited to gas management which is a crucial portion of any dive. The more involved the dive, the broader its objectives, the more important responsible gas management becomes. Maturity and judgment reinforce the concept of proper gas management. Most open circuit technical divers, and all overhead environment divers, observe the gas management rule known as the Rule of Thirds. The cave diving community developed the Rule of Thirds after analyzing their accident history. The Rule of Thirds is conservative. It was designed to be so. More importantly, experience has taught us that it works. In CCR diving the plan should be to exit with one third of the on-board oxygen supply gas and we carry team bailout adequate to get one and one half divers to the surface.

"Technical diving is a hostile environment for dependent divers!"

Every OC gas management rule devised depends on individuals functioning "normally". They must swim normally, breathe normally and function as expected. While engaged in an OC bailout unanticipated variations caused by the environment or changes in divers' abilities cannot occur. This means that events such as unexpected currents or having to maneuver through restrictions must not deter the diver's proficiency.

- **Establish gas management procedures**
- **Decide on the limits of the dive**
- **Determine team size & responsibilities**
- **Determine team member compatibility**
- **Know the configuration of fellow divers**
- **Plan for "what ifs" and team safety**

If divers who have bailed out to OC are forced to increase their swim pace, they will also increase gas consumption. Other changes in respiratory patterns, such as response to mental and physical stress, will also increase gas consumption. When divers slow their pace, gas consumption is reduced.

Once again, this is where mental and physical conditioning comes into play. With mental discipline and good physical fitness, it is much easier to remain "normal" during a stressful event. A physically conditioned person will have much less increase in gas consumption with increased workloads than an out of shape diver.

A diver who does not maintain good cardiovascular efficiency will experience tremendous changes in his/her OC gas consumption when going from light effort to harder workloads. A diver who maintains a cardiovascular training program will experience significantly lower changes in his/her respiratory minute volume when switching from light to heavy exertion than a comparable individual who does not train on a regular basis. The diver who is a weekend warrior and a couch potato during the week will also have less endurance and is more likely to experience increased use of gas when fatigued.

The size of the dive team will dictate effective OC bailout gas management. Obviously a two-person dive team is the most efficient from a dive performance standpoint. It needs less communication and requires less choreography. Both divers know where each other are. Swim pace is easier to regulate. A small team reduces the level of environmental management needed. For example, silting is just one of many factors that's easier to anticipate and prevent.

On the other hand, there are strong arguments to support the advantages of a three-person dive team. The group bailout gas supply can go much further when shared between three people. Two people are usually better able to rescue an individual in trouble.

When computing a team bailout gas management model, compensate for variations in both breathing volume (respiratory minute volume - RMV) on OC and varying tank capacities. In addition, plan out the known gas volumes for the dive. If a dive has a three-person team, the dive gas is matched automatically.

Photo by Tom Mount

When planning with known gas volumes, refer to IANTD Table 12 in the *Technical Encyclopedia*. This table will allow you to determine the actual volume of gas available to you. For example, an OC diver accompanying the CCR divers has 2,000 psig (136 bar) in double 121s (double 19 liters) rated at 2640 psig (180 bar). By checking the tables, you can see the diver actually has the equivalent gas volume of double 91.7s (double 15 liter tanks at rated volume).

This process provides the ability to plan gas duration based on the diver with the greatest RMV being able to exit a dive while sharing bailout gas from the team gas. To use the IANTD Tables, simply determine your *RMV*. Most divers do this while swimming at a moderate pace and a fixed depth, for 10 minutes. This value is then converted into a surface rate. A "resting rate" can also be determined. To develop a resting rate, breathe on SCUBA for 10 minutes while resting. Adjusting the surface rate to account for different energy outputs can develop variations. For example, gas consumption will be greater in a current than calm water.

The gas plan you use must be developed from a swimming-based surface rate, versus a resting rate. It must be fine tuned by adjusting anticipated gas consumption against the environmental factors you expect to encounter. Experience has taught us this method is consistently accurate for planning dives involving a lot of swimming. To do this correctly, all dive team members must know their individual RMVs for bailout planning and their oxygen metabolism for planning dive durations.

Determine bailout gas duration required for the dive plan by anticipating the planned distance traveled,

Notes:

coupled with gas consumption. Let's look at two divers who are planning a dive into a moderate outflow cave. The example below employs a cave dive, because cave dives generally require more consistent swimming than open water dives.

Example:

- Swimming into a cave, the divers will swim at a pace of 50 feet (15 meters) per minute.

- From gas planning, it has already been determined that the oxygen turn time based on the diver with a 1.5 L per min oxygen metabolism rate will be 132 minutes. During this period the divers will travel 6,600 feet (1,980 meters).

- The planned dive depth is 100 feet (30 meters). Assume the exit speed will be 75 ft. (22.5 m) per minute thus the team will exit in 88 minutes.

- However if one of the team members is forced off the loop at the maximum point of penetration how much OC gas will be needed to exit.? Assume this diver is the one with the highest RMV of the team and it is a surface equivalent of 0.7 ft^3 (20 L) per minute.

- At 100 feet (30 meters) the diver breathes 2.8 ft^3 minute (80 L) per minute, The exit time is 88 minutes this a total of 246.4 ft^3 (7040 L) is needed. For team bailout the team should carry 1.5 times 246.4 or 370 ft^3 (10,560 L). In a 3-person team each diver would be responsible for 124 ft^3 (3520 L) of gas. In a cave, portions of this gas could be staged.

- However, what happens if the divers slow their return due to an emergency such as a silt-out or environmental problem? In this event, let's say the exit speed is at 25 feet (7.5 meters) per minute. The exit will take 264 minutes. With the slowed return the divers would need 739.2 ft^3 (21,120 L) of bailout gas. This means they would not make an exit on the amount of gas carried. The same would be true on an OC dive. So it is very important that the exit speed equal or exceed the ingoing speed. A big advantage of CCR diving is there is less probability of delayed exits as the diver may swim freely instead of being tied to another diver by a long hose.

Avoidance is a key principle of technical diving. In this case, however, avoidance does not mean ignoring a potential problem. It means knowing what constitutes a small problem and what doesn't. It means knowing that a "tiny" free-flow could become a major problem. It means having the common sense to know if one part of your gas supply is not working properly, turn it off and use your alternate source. It means having the discipline to anticipate, to think ahead, and to immediately neutralize the source of problems.

An advantage for CCR divers is that work rates make little difference on the gas used in the cylinders, thus allowing gas management to be more precise. However, if a diver must bailout then all the things that apply to OC gas usage come back into play. For this reason the team's total bailout gas must be adequate to get 1.5 divers to the surface or to another staged dive gas. Each diver in the team must have adequate bailout gas factored into the team's gas to fulfill this requirement. All divers in the team must be competent in exchanging bailout out cylinders or alternate methods of gas exchange. For team safety, a diver forced off of the loop must surface. Ideally in the future, each diver will have a bailout rebreather for this purpose. If someone is diving in a non-team situation or there is a high probability that team members will become separated, then the diver must personally carry sufficient bailout gas to reach the surface or other staged gas.

In addition to the bailout gas management issue, divers need to plan the dive so that no one has less than one third of their oxygen supply gas upon surfacing or reaching a staged oxygen cylinder. To accurately plan for this, each team member's oxygen metabolism rate must be known. There is a significant variation between individuals with some divers using as much as double the amount of oxygen as their buddy, due to metabolic needs. Another factor is how efficiently he/she dives the unit. If an ADV is always used, you will breathe more oxygen each time the loop reaches a minimum volume because the diluent will add gas. This addition will lower the PO_2 and then the solenoid will fire to restore the PO_2.

In bailout planning, ensure each team member has a dive computer or dive tables for the dive plus a back up computer, and/or back up dive tables. Also, as divers may have more than one style of CCR in the team, be sure the plan includes team bailout management that considers the following:

1. The valves may not permit gas exchanges between some different CCR designs, so an alternate gas management plan must be developed to deal with this.

2. It is possible that all divers may not have the same diluent or bailout gases. In this event the decompression procedure and the ability to use bailout gases other than those the diver may carry must be included into the dive plan.

3. If the team dives consistently with each other prior to arriving at the site, preplanning should ensure that the divers have compatible bailout gases and have planned around any inconsistencies in valve variations from one CCR to another. This may require adding extra low-pressure hoses to be compatible with each team member's needs. Each diver may need to add/change valves on their unit so the team is compatible in this area.

4. Many divers (including the author) prefer to use all low-pressure fittings that are interchangeable with the counterlungs, BC, and the dry suit. In addition if all team members are of the same philosophy, then compatible fittings can be planned for the entire team.

In a dive team, if a diver has loop failure, the "off the loop diver" will go to their OC bailout. Then once 50% of the bailout gas is used, they will switch stages with another diver until 50% of this gas is used, and so on. This process will be repeated as dictated by the situation, but will ensure all divers have adequate bailout gas to reach the surface or other stages gases. If it is a three person team the "off the loop "diver will be positioned between the other two divers enabling the bailout gas to be rotated between all three divers.

Planning for Teams Using Mixed Equipment

Diving with a team composed of people who are diving Closed Circuit, Semi-closed Circuit, and Open Circuit is definitely an exercise in "Multi-Cultural Diversity"! It can work, but it will only work well if the members of the team display tolerance, understanding, and a willingness to accommodate the "special needs" of the other team members.

Notes:

Photo by Jim Kozmik

Specifically, this will be one of the most complex and difficult dive planning sessions that the team will have to participate in. By following the procedures laid down in this text, the team members will find that the plan will be simple, easy to follow and above all safe. The key to the project is finding a baseline, which will be established by the physical limits of the equipment involved and begin mission planning from that point.

Some people take the approach that diving in "mixed" teams should be avoided, but experience reflects that this is not an uncommon practice. When teams are mixed, the OC diver is the one with the greatest disadvantage since he/she usually has limited or no understanding of the rebreathers and their operating requirements.

Logically the first step is to provide the OC diver with an overview of how the rebreather functions (CCR, SCR, or both). This must include a quick review of issues with the partial pressures of gases, and the fractions of gases in the mix on SCR. The significance of gas supplies, gas duration and canister limitations should also be covered. Then the OC diver should be introduced to recognition of rebreather problems and how they are solved. As many OC divers have great concern with the operating procedures and bailout systems a short course will need to take place explaining these issues. The OC diver in a team that has one or more CCR divers should be aware of the bailout options for the CCR diver should they have a malfunction of the system. Thus it must be explained that the CCR diver has a progression of bailout scenarios.

The options include:

1. If at a constant depth the diver has been diving minimum loop volume, remain on minimum loop until a depth change occurs.
2. Dive the CCR in SCR mode.
3. Use Open Loop bailout.
4. Bailout to OC.
5. Bailout to buddy's OC.

Of course this will take a brief description of the process. In some cases, the diver may have a bailout CCR, and if that is the case it will become the first option.

Explain to the OC diver how adequate bailout is predicted and the 1.5 minimum rule. Provide the OC diver with an example: how much gas would an OC team need to exit or return to the surface from a maximum point of penetration if one diver has a total loss of gas, requiring them to share gas. The OC diver is utilizing the rule of thirds, so the plan maintains a gas supply of one third for the buddy to use or to overcome problems on the dive.

Rebreather bailout principles are based on similar concepts. However when using a rebreather the OC gas plan does not have to include gas for use up to a point of failure (as in OC diving). In its broadest application, it also assumes the same constants the OC rule of thirds does, controlled RMV, swim rate and single system failures. The rebreather bailout concept also allows for a solo diver or a high probability of team separation. Each diver, based on their RMV, carries adequate OC gas or a bailout rebreather to surface or get to the staged dive gases. For normal confident diving, the team will remain intact until the end of the dive. Their gas is planned to provide OC bailout to get 1.5 divers out/up, or to a staged bailout gas.

EXAMPLE:

Planning a CCR technical dive (using the same exit gas reference as on the OC dive):

1. The CCR diver or team will determine the amount of gas needed to exit or reach staged gas by the diver with the highest RMV (unless using a bailout rebreather).

2. In this case we will assume the emergency gas needed for an "out of gas" or "off the loop" diver is 40 ft^3 (1200 L). The bailout gas is for bailout or other emergencies and can be given to the OC diver should they have total loss of gas.

3. If the team consists of more than one CCR diver(s) and one OC diver, then the CCR team would collectively carry 40 ft^3 (1200 L) times 1.5 or 60 ft^3 (1800 L) of team gas.

4. Each of the two CCR divers would carry a minimum of 30 ft^3 (900 L) of bailout gas. In an emergency the bailout gas would be rotated between the divers. This actually provides an additional 20 ft^3 (600 L) of reserve gas.

5. If the dive team consists of one OC diver and one CCR diver, then the CCR diver must carry adequate bailout gas to exit or reach staged dive gas. In this case the CCR diver would carry 40 ft^3 (1200 L) of gas. This provides the same emergency gas, as needed for the team of two OC divers.

Notes:

When either diver is forced to go to a gas supply other than their primary gas, the CCR diver could use the OC diver's long hose and the exit would be the same as on any OC dive. If the OC diver is forced off their system, simply go to the CCR diver where they will most likely be given the stage cylinder with the 40 ft^3 (1200 L) of gas. A stage hand-off to the distressed diver may take

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a brief moment, but then allows a simpler exit and less time is wasted than with an OC diver on a long hose. The stage hand-off eliminates the slow swim times that a long hose would require and problems associated with narrow openings or restrictions, etc.

On some rebreather systems the bailout gas is configured to go directly into the loop. In such a system, the rebreather diver may provide a long hose (preplanned) instead of handing off a stage.

Many rebreather divers, such as the author, prefer to carry two smaller cylinders that can be rotated in a manner to always allow the donor diver(s) to have some form of bailout gas. This also gives more flexibility if more than one diver experiences a system failure, especially considering the probability that two persons would have total system failures at the end of a dive. The 1.5 times gas needed should cover multiple failures and be easily managed if each diver carries their bailout in more than one cylinder. If the bailout required is 40 ft^3 (6 L), carry two 20 ft^3 (3 L) cylinders.

Typically on CCR dive teams, once a diver uses 50% of their bailout gas they will exchange cylinders with another CCR diver and once again use 50% of that gas supply. If it is a three-person team, go to the third diver, switch, and repeat each time 50% of the gas in the cylinder is used. If it were a two-person team then the rotation would be between the two persons. On a team with an OC diver, if the CCR diver is the one with the problem they will use 50% of their cylinder, then go to the long hose of the OC diver, use 50% of his share of the OC diver gas, and then back to his cylinder - rotating back and forth in that manner. If another OC diver or rebreather diver is in the team, that diver will also be included in the rotation for gas. If the OC diver has had a problem, simply take the CCR diver's bailout gas. If it is a 2-person team, keep the cylinder until reaching the exit, surface, or other staged dive gas. If the dive has a three-person team the OC diver would follow the same rotational practices as the rebreather divers.

Another method, considering the difference in gas management between CCR and OC divers, is that the OC diver carries bailout gas. Plan the dive in the same manner as the rebreather diver. The primary gas supply will be used for the dive and the bailout stage(s) will be used for emergencies.

Advantages of the OC diver using the bailout concept:

1. Increases dive capability (in this case he would have two primary gas options).
   a. Devote the entire primary gas supply for use on the dive.
   b. Use 80% of the primary gas for the dive with 20% for emergency use.

2. Carry bailout gas in addition to the primary gas based on the same rules as the rebreather bailout.
   a. If diving solo or with a high probability of separation, carry adequate personal bailout gas to reach exit or staged dive gas.
   b. If confident the team will remain intact, carry adequate team bailout for 1.5 divers. Apply distribution as explained previously.
   c. Ideally carry multiple (2 or more) smaller cylinders, in an emergency they can be rotated to always ensure that each diver has onboard bailout.

Use this approach especially when multiple cylinders are carried. It allows a better chance of survival in a multi systems failure situation.

An SCR diver using an active (mass flow) system is limited by the gas supply, flow rate and canister duration. A diver on a passive SCR will be limited by gas supply based on the ratio of the unit with the diver's RMV factored in, and canister duration. The OC diver is limited by their RMV and gas supply. The CCR diver is limited solely by canister duration.

Photo by Tom Mount

The biggest issue is that the OC diver must be able to recognize CCR or SCR problems and understand the corrective action taken by these divers. Another point, in this scenario there is a higher probability of each diver being on varying gas mixtures. However, if the dive is planned as a team dive the bailout gases should be matched to the bottom mix used by the OC diver(s). A bailout by the OC diver to a rebreather diver's stage will not add to the decompression needs of the OC diver.

In an ideal world a rebreather diver will educate the OC diver on the rebreather to an adequate level regarding the different systems between everyone on the team. The OC diver may feel more comfortable if the CCR diver displays his/her PO_2 read-out. This will ensure that the OC diver knows that the partial pressure of oxygen is acceptable. Also the OC diver may wish to check that the CCR diver is periodically checking his/her displays

On decompression, the divers will most likely have variations in the stop times and total run time of the dive. Most likely the CCR diver will complete decompression first, especially on a multi level dive, then the OC diver and lastly the SCR diver.

Additional gas switches by the SCR and OC divers can be scheduled to coordinate the run times.

In summary, prior to commencement of the dive, review all the objectives. During this phase of the plan, ascertain that each diver is aware of the responsibility assigned to him or her. If it is a complex skill, rehearse it through land drills as a team and visualize it. At the same time, discuss the absolute limits of the dive.

In addition to gas management, consider factors such as partial pressure of oxygen, narcosis loading, gas density, decompression duration and contingency factors.

For Open Circuit diving under no circumstance should a bottom mix PO_2 exceed 1.4ATA, and it is prudent on longer dives to drop to 1.3ATA. For decompression, a maximum of 1.6ATA is to be observed. On exceptional exposures, the dive gas design must allow for a total exposure to remain within team and physiological safety standards. Some projects actually limit the bottom mix to less than 1.35ATA and decompression mixes to 1.50ATA. Usually, these projects use multiple gas changes on stops and stay close to a range of 1.2 to 1.45ATA throughout the entire stop times. Remember, to plan both the MOD (maximum operating depth) and TOD (target operating depth) limits for oxygen, nitrogen (narcosis limits) and gas density.

Define other limits such as penetration on a dive, duration, burn time of DPVs, lights and other support equipment used on the dive. Basically, sit down and detail all the events in the proposed dive and define the minimum and maximum risk values of each. The limits should remain within the agreed on team values, provided they are all within the personal risk acceptance of each individual.

Be careful not to challenge egos when planning complex dives. This is a time when each diver's self and team honesty is paramount to the safety of the project. Be certain the team members are compatible. On technical diving projects, one must be comfortable with the abilities of the team, have trust and respect for the members, and they should have compatible personalities. Remember that each of the members should be self-sufficient, yet aware that in unusual circumstances their lives may depend on a coordinated team effort.

Prior to entering the water, make certain that each diver is totally aware of each other's equipment configuration and its operational parameters. Each portion of the system is to be pre-dive checked and verified by a team member (buddy). When it is possible, do an in-water safety drill to ascertain that all components operate correctly and that each diver can use the buddy system. Divers must breathe from each other's second stage to be handed off and verify the functionality of equipment of the buddy diver. This act is a vital part of pre-dive checks. It should be approached in a checklist fashion.

> **Mother Nature is often fickle... So you must be prepared to alter and to modify the dive plan.**

- Changes in current
- Changes in visibility
- Changes due to upline problems
- Changes due to team reaction

List of every "what if" scenario that may effect team safety. Define and rehearse corrective steps mentally and physically, if possible. This list must include all safety parameters and all possible problem areas that the team can identify. Be creative. Once the list is developed, discuss all solutions and develop a "what if" plan of action for each item as a team. After this, verbally go through each item at least three times and then visualize safely correcting the "what if" situations. Once this is accomplished, put it to bed. Then, visualize and enjoy a safe and productive dive.

The final aspect of dive planning is in-water updates. Murphy's Law is always with us. Frequently, dive plans require alternations due to changing water conditions. Therefore, remain open-minded when beginning a dive and prepare to modify the dive plan as dictated by the environment and conditions.

Once the dive begins, allow for flexibility in performance. Mother Nature is often fickle. The dive may offer the unexpected, and you must be prepared to alter and to modify the dive plan. A degradation of visibility may provide grounds for altering the dive plan while in the water; if so, have that included as an agreed dive plan objective. Changes in the type of, the severity of, or the direction of current may be a sufficient cause for modifications in an existing dive plan. If a boat breaks anchor, or a guideline is broken, or other factors that influence either the exit or ascent of a dive, these are grounds for modification or cancellation of a dive.

You will also need to anticipate behavioral changes within the dive team. Simple things such as one diver becoming uncomfortable will modify the dive plan. Accident potential increases when you fail to modify the dive plan because of a diver's behavioral changes.

Awareness is the critical component in making a command decision to modify the plan of a dive already in progress. As you explore and discover, don't forget to periodically observe the members of your dive team. Set up a plan of intermittent contact.

Observation and communication play key roles. Observation helps you to know when a diver starts "slipping." Communication overcomes the hesitancy of divers to tell you they are having a problem.

Guilt associated with failure is a key threat to dive safety. Divers will frequently feel guilty if they cause a dive to be terminated. Feelings of guilt, combined with a "threatened ego," produce a potentially dangerous combination if the dive is allowed to continue. While diving, not every change in a team member is obvious. You must be aware of subtle changes that may occur. These would involve recognizing changes in coordination, swimming style or rhythm, and breathing patterns.

Maturity and sound judgment play key roles in personal success and diving ability. The smart diver knows that cancellation is not the end of the world. Once they learn a dive cannot be accomplished as planned, they will terminate the present dive. They understand that a new plan must be developed to incorporate what has been learned. He/she knows that the price of continuing an unsafe dive skyrockets. It's not only foolish; it's deadly to continue diving with a marginal safety factor.

Conclusion

In summary, a safe dive plan requires divers to gather all information pertinent to the dive site. The entire dive team needs to discuss the dive comprehensively and establish a team plan. Each participating diver must search his/her mind and develop a personal plan of action. This personal plan should be based on self-sufficiency. It must allow for self-rescue ability and team rescue capabilities. Gas Management Rules must be carefully and comprehensively developed from actual field experience.

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Chapter 2 - Oxygen & The Diver

by David Sawatzky, M.D.

Oxygen is a vital necessity for life, and a frequent cause of death in divers. In CCR diving, hypercapnia (too much CO_2), hypoxia (too little O_2) and hyperoxia (too much O_2) are the three big problems. The physiology of O_2 and O_2 toxicity is fairly complex, but it is worth learning as much as possible so that you can dive in a safer fashion. In this chapter we are going to look at the physiology of O_2, acute hypoxia, O_2 toxicity, acute hyperoxia, and some of the potential longer-term effects of hyperoxia.

Physiology of O_2 Transport at the Surface

Oxygen has atomic number 8, which means the nucleus is composed of 8 protons and 8 neutrons. It is a colorless, odorless, tasteless gas and by volume, air is composed of 21% O_2. Therefore, the partial pressure of O_2 on the surface is 0.21 ATA, or approximately 160 mm Hg (1 ATA is 760 mm Hg *x* 21% = 160 mm Hg). Oxygen normally exists as a molecule made up of two oxygen atoms.

When we take a breath, the air we inhale is mixed with the air that remained in the mouth, airways and lungs at the end of the last breath. This air contains approximately 17% O_2 and 4% CO_2. In addition, water vapor is added to the inspired air until it is 100% saturated at body temperature. The net effect is that the gas in the alveoli has a partial pressure of O_2 (PO_2) of around 105 mm Hg.

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It takes a small difference in PO_2 to drive the O_2 across the alveolar walls into the blood, and some blood passes through the lungs without completely equilibrating with the air in the alveoli so that the arterial blood leaving the lungs and being pumped by the heart to the tissues of the body has a PO_2 of around 100 mm Hg in a normal, healthy person.

However, PO_2 is only part of the story. What we really care about is the amount of O_2 the blood is carrying to the tissues. At a PO_2 of 100 mm Hg, approximately 0.3 ml of O_2 will dissolve in every 100 ml of blood. This is a trivial amount of O_2 and not nearly enough to sustain life. The secret is hemoglobin (Hb). Hemoglobin is a complex protein that is designed to carry 4 molecules of O_2. It is contained inside Red Blood Cells (RBC) and gives blood its' red color. The amount of Hb in blood varies from approximately 12 to 18 grams per 100 ml with 15 grams being a normal value in males (slightly lower in females). One gram of Hb can carry 1.36 ml of O_2 and at sea level in a normal healthy person, Hb is approximately 97% saturated with O_2 when it leaves the lung.

Therefore, the Hb in every 100 ml of blood can carry 15 x 1.36 x 0.97 = 19.8 ml of O_2! When we add the 0.3 ml of O_2 dissolved in the plasma, each 100 ml of blood can carry roughly 20 ml of O_2. How much O_2 is off loaded in the tissues depends primarily on blood flow and how much O_2 the tissues are using. In most tissues, the blood leaving the tissues has a PO_2 of 40 mm Hg. When the O_2 requirement of a tissue increases (a muscle starts to work), the tissue has a limited capacity to off load more O_2 from the blood. The primary mechanism the body uses to deliver more O_2 to a working tissue is to increase the amount of blood going to the tissue. For example, a muscle working at maximum capacity will have approximately 100 times as much blood flowing through it as the same muscle at rest.

It is also important to understand that tissues cannot 'store' a significant amount of O_2. Muscle contains a small amount of myoglobin. Myoglobin is a protein like Hb, but it can only bind one molecule of O_2. The rest of the O_2 in tissues is dissolved in the fluid, and we have already seen that very little O_2 dissolves in body fluids. Finally, O_2 is used in the cells to generate Adenosine Triphosphate (ATP). ATP is the molecule that actually 'makes things happen', like causing muscles to contract. A small amount of energy is also stored as creatine phosphate (CP) but the combined energy stores of ATP and CP will only supply enough energy for a hard working muscle for a few seconds. The bottom line is that tissues need a continuous supply of O_2 to be able to continue to function.

Approximate Oxygen Stores For A Person Breathing Oxygen at Sea Level	
450 ml	Oxygen in the Lungs
850 ml	Oxygen in the Blood
50 ml	Oxygen Dissolved in Body Fluids
200 ml	Oxygen Bound to Myoglobin

When asleep (totally at rest), a 70 kg (150 pound) person requires about 250 ml of O_2 per minute. When that same person is exercising at their maximum capacity, they will require up to 4,000 ml of O_2 per minute (if they are a highly trained athlete). An average, reasonably fit technical diver will require 3,000 to 3,500 ml of O_2 per minute at maximum exercise.

The reason I went through the above explanation is that it is critical for a technical diver, and especially a CCR diver to fully understand what happens in the normal person on the surface so that they can understand what happens when we breathe gases other than air, and when we breathe those gases under increased pressure.

Physiology of O_2 Transport & Absorption when Diving

Does breathing Nitrox deliver more O_2 to the cells? When we are breathing Nitrox 40 on the surface (PO_2 of 0.4 ATA), the PO_2 in the alveoli will be approximately 200 ml Hg, or about twice what it is when we are breathing air. Therefore, the blood leaving the lungs will have about 0.6 ml of O_2 dissolved in every 100 ml of blood, and 19.8 ml of O_2 attached to Hb in every 100 ml of blood. The total amount of O_2 carried by the blood will have increased only 0.3 ml for every 100 ml of blood, even though we have doubled the inspired PO_2! This point is VERY important. Breathing O_2 at elevated pressures does not significantly increase the amount of O_2 being carried by the blood. What happens in the tissues? The amount of O_2 in the tissues does not change significantly, but the PO_2 will increase. The important point about using Nitrox is not that we are breathing more O_2, but that we are breathing less nitrogen.

Extending this discussion to CCR diving, we know that PO_2 is kept constant by the rebreather. If we use a set point of 1.3 ATA, we will have a PO_2 in arterial blood roughly 6.5 times higher than breathing air on the surface. Therefore, we will have 6.5 X 0.3 = 1.95 or 2 ml of O_2 dissolved in the plasma of every 100 ml of blood. This is still a very small amount compared to the 20 ml of O_2 carried by the Hb in the same 100 ml of blood. Even though we are breathing the equivalent of 130% O_2, the amount of O_2 being delivered to the cells is not significantly changed.

As with Nitrox, the primary reason we dive with an elevated PO_2 when diving rebreathers is to reduce the amount of inert gas we are breathing and thereby absorbing during the dive. A lot of technical divers 'push' the PO_2 during the bottom phase of a dive. Does this make any sense? Let's look at an example. We are going to do a dive to 300 fsw (90 msw). If we use a PO_2 of 1.6 ATA, we will be breathing 8.4 ATA of inert gas (84%). If we use a set point of 1.3 ATA, we will be breathing 8.7 ATA of inert gas (87%). The risk of having an O_2 convulsion with a PO_2 of 1.6 ATA is far higher than with a PO_2 of 1.3 ATA. It makes no sense to dramatically increase the risk of an O_2 convulsion to reduce the inert gas percentage by 3%, as this will have a small effect on our required decompression time.

Another vital factor is O_2 absorption and use when diving. We mentioned above that the average person would use between 500 ml and 3,000 ml of O_2 per minute, depending on their activity level. A vital fact to understand when CCR diving is that the amount of O_2 used by the body does NOT CHANGE WITH DEPTH! This is critical. When you are working while diving, the muscles require the same number of molecules of O_2 to make ATP as they do on the surface. Depth is not a factor.

When you increase the PO_2 of the inspired gas, slightly more O_2 will dissolve in the blood, but there is no significant change in the amount of O_2 delivered to the cells. So who cares? CCR diving is unique in that only the O_2 your body uses is added to the loop (ignoring O_2 lost in bubbles, but then there shouldn't be any at constant depth should there!).

So what happens when we are sitting breathing on the surface? There are approximately 6 liters of gas in your lungs at full inspiration, and very roughly 4 liters of gas in the scrubber and loop for a total of 10 liters of gas. If we use a set point of 0.7 ATA, how long will the O_2 in the system sustain us at light work (1.0 liter of O_2 per minute)? We have 10 liters of gas at 1.0 ATA, 70% is O_2 so we have 7.0 liters of O_2 that we are using at 1.0 liter per minute, and so the O_2 will last 7 minutes. Of course we will have to add diluent to maintain the breathing volume as the O_2 is absorbed, but that will add more O_2 and make the gas last even longer.

Photo by Curt Bowen

If we take the same situation at a depth of 300 fsw (90 msw), the gas will be 10 times as dense. Therefore the 10 liters of gas in the loop and our lungs will contain 10 times as many molecules. **The increased molecules still represent the same mix and the oxygen is metabolized at the same rate. Thus the PO_2 will decrease at the rate it would at a more shallow depth.**

Acute Hypoxia

When diving CCR, one of the primary concerns is having enough O_2 in the breathing mix. There are several ways the concentration of O_2 in the breathing mixture can decline, including solenoid failure closed, O_2 tank turned off, O_2 tank empty, O_2 tank containing something other than O_2, electronic failure, etc. Our purpose here is not to review these failure modes, but to examine the physiology of what is happening when they occur.

For discussion purposes, let's look at what happens to the CCR diver who leaves the O_2 tank turned off and does not check their gauges. They get dressed and start breathing on the rebreather. The gas in the rebreather is most likely air, or a fairly high percentage Nitrox if they have calibrated their O_2 sensors. As they continue to breathe, the CCR will remove the CO_2 they produce and the PO_2 will slowly fall. For several minutes, there is no way that the diver will be able to tell this. They then dive into the water and start to descend. As they descend, the gas in the loop will be compressed and they will add diluent (air) to maintain a breathable volume of gas. This fresh gas adds O_2 to the breathing mixture. In addition, as the diver descends the increasing pressure will increase the PO_2 in the breathing loop and the diver will have lots of O_2. Once the diver reaches the bottom, the PO_2 in the loop will very slowly fall. Eventually, they will become hypoxic, but this might not happen until 20 minutes or more into the dive!

Why does it take so long? The first reason is the pure physics of the situation as explained above. This causes the PO_2 to remain elevated for a very long time. Factors include the initial PO_2 in the loop, the initial volume of the loop, the rate at which the diver descends, the rate at which the diver uses O_2, the PO_2 of the diluent, the amount of diluent that is added, etc.

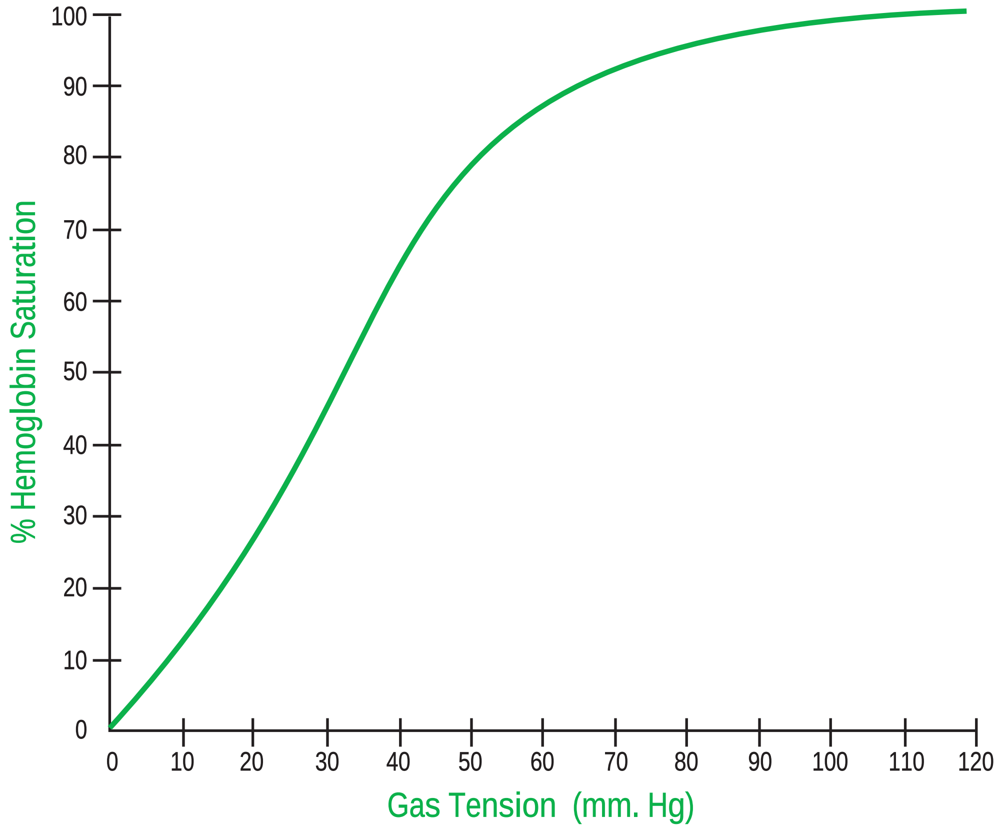
Once the PO_2 drops to 0.21 ATA there are some physiological changes that enable us to tolerate even less O_2 until the PO_2 drops to less than 0.16 ATA at maximum exercise, or until about 0.12 ATA at rest.

As we reduce the PO_2 in the inspired gas, the PO_2 in the alveoli and therefore the arterial blood starts to fall. The body is very well designed however and Hb is very effective in savaging O_2 from the gas in the lungs, even when the PO_2 is less than normal. The Hb/O_2 dissociation curve shows that even when the PO_2 has fallen, the Hb is still saturated. In this part of the curve, a relatively large fall in PO_2 causes a small fall in Hb saturation. Therefore, virtually a normal amount of O_2 is being delivered to the tissues by the blood, even though the PO_2 is less than normal.

If we are exercising very hard, and therefore require lots of O_2, we will be completely OK until the inspired PO_2 is less than 0.16 ATA (16% O_2 on the surface). If we are resting, we will not notice anything until the PO_2 falls into the range of 0.12 ATA!

All good things have a cost however, and the cost of this flexibility in inspired PO_2 is that once we become hypoxic, the amount of O_2 that will combine with Hb and therefore the amount of O_2 that will be delivered to the tissues falls very rapidly. This is represented by the steep part of the Hb/O_2 dissociation curve where a small decline in PO_2 causes a large decline in Hb saturation.

The brain is a tissue that is totally dependant on O_2 to function. Most of the other tissues in the body have alternative biochemical pathways that do not involve O_2 to generate small amounts of energy. These pathways are very inefficient, and they generate waste products that build up and ultimately limit the ability of the cells to function, but they do allow muscles for example, to work for a few minutes at a level greater than can be supported by the amount of O_2 being delivered to the muscle by the blood. The brain does not have this capability and it also does not have the small O_2 stores that muscle contains (no myoglobin and very little CP). The end result is that the brain is very sensitive to inadequate O_2 supplies and it is the cause of most of the signs and symptoms of hypoxia.



Signs & Symptoms of Hypoxia

Loss of consciousness is often the first sign of hypoxia, especially if the fall in PO_2 is rapid. Other signs include poor performance and in-coordination. Symptoms of hypoxia include euphoria, over confidence, apathy, fatigue, headache, and blurred vision. Hyperventilation is usually not present if the PCO_2 is normal. Defective memory and impaired judgment are common. These often cause the diver to respond inappropriately to an emergency, and to ignore other signs and symptoms of hypoxia. Therefore, loss of consciousness is very common in hypoxic divers.

A further problem is that many of the signs and symptoms of hypoxia are the same as those of narcosis, O_2 toxicity, and elevated PCO_2. In addition, these problems are additive. For example, if the PCO_2 is slightly elevated (scrubber starting to break through) and the PN_2 a little high (diving a bit deep on Nitrox), the resulting mental impairment will be far worse than expected from either one alone. If the PO_2 is also slightly high or low, the diver will be in serious trouble. This is why the first response to any perceived problem while diving CCR should be to go OC on a safe gas until you have determined exactly what the problem is and have resolved it. It is also why most CCR units have alarms that go off when the PO_2 drops below 0.5 ATA, hopefully the diver will be able to recognize and correct the problem before the level of hypoxia impairs their thinking processes.

		Air (21 & O_2, 79% N_2)		Nitrox (40 & O_2, 60% N_2)	
Depth (fsw/msw)	Pressure (ATA)	pO_2 (ATA)	pN_2 (ATA)	pO_2 (ATA)	pN_2 (ATA)
surface	1.0	0.21	0.79	0.4	0.6
33 / 10	2.0	0.42	1.58	0.8	1.2
66 / 20	3.0	0.63	2.37	1.2	1.8
99 / 30	4.0	0.84	3.16	1.6	2.4
132 / 40	5.0	1.05	3.95	2.0	3.0
218 / 66	7.60	1.6	6.00	3.0	4.6
297 / 90	10.0	2.10	7.90	4.0	6.0

Hypoxia of Ascent

When we descend while diving CCR, we must add diluent to the loop to maintain a breathable volume of gas. At the same time, the gas in the loop is being compressed and the PO_2 is climbing. For example, if we used no O_2, added no diluent, and left the surface with a PO_2 of 0.7 ATA, when we arrived at 30m (100 ft) the PO_2 would be 4 X 0.7 = 2.8 ATA. If we balance our rate of descent, work rate, and addition of diluent, it is often possible to leave the surface with a PO_2 of 0.7 ATA and arrive on the bottom with a PO_2 of 1.3 ATA, without changing the set point from 0.7 ATA, or injecting any pure O_2.

When we ascend, the gas in the loop is expanding and we must vent gas. At the same time the PO_2 is dropping. For example, if we leave the bottom at 30 m (100 ft) with a PO_2 in the loop of 1.3 ATA, used no O_2 and added no O_2, the PO_2 would be 1.3 ATA / 4 = 0.325 ATA when we arrived on the surface. Of course we use O_2 during ascent so the real PO_2 would be even less. A trick while CCR diving is to make sure you are at minimum loop volume when you start your ascent, and to vent frequently during ascent to maintain minimum loop volumes so that the unit will have to inject less O_2 to maintain the PO_2 as you ascend.

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Oxygen Toxicity

In Open Circuit technical diving, O_2 toxicity has caused accidents and fatalities. In CCR diving, O_2 toxicity is also a major cause for concern. To have a reasonable understanding of the danger of excessive O_2, we have to understand the physiology of O_2 toxicity.

The first and most basic point is that molecular oxygen is not toxic! The problem is that whenever molecular O_2 exists, it forms other substances known as 'oxygen radicals'. Oxygen radicals are highly reactive molecules, formed from oxygen, which contain at least one extra electron. These molecules are formed from collisions between oxygen and other molecules, and as a result of metabolic processes in the cells. Examples include superoxide anions, hydrogen peroxide, hydroperoxy and hydroxyl radicals, and single oxygen. Oxygen radicals will bind to and react with the next molecule they come in contact with, often damaging or changing that molecule. Therefore, whenever you have O_2, you will have O_2 radicals. The number of O_2 radicals is proportional to the partial pressure of O_2.

There are hundreds of specific chemical reactions that oxygen radicals can be involved in that damage the cell but in general terms there are three ways that they cause damage. The first is through inactivation of enzymes. Enzymes are proteins that work as catalysts, causing reactions to occur that would not normally occur at body temperature. They do this by holding the two molecules that are to react in exactly the right orientation to each other so that they join. The resulting molecule is released and the enzyme starts again, repeating the process thousands of times. If the shape of the enzyme is changed, the molecules will not be held in the right orientation and the reaction will not occur. Oxygen radicals cause cross-linking of sulphydryl groups, thereby changing the shape of the enzyme and inactivating it. They also cause changes in the shape of proteins responsible for transport of ions in and out of the cells across the cell membrane, stopping them from functioning. Finally, oxygen radicals cause peroxidation of the various lipids in the cells.

All cells in oxygen breathing animals have ways to inactivate oxygen radicals and to repair some of the damage done by them. The two main defenses are superoxide dysmutase and catalase. Both of these enzymes help maintain a good supply of reduced glutathione. Reduced glutathione has many sulphydryl groups and oxygen radicals will bind to them, and thus be unavailable to cause damage to the cell. Vitamins E and C are also anti-oxidants.

Oxygen radicals are not only important in diving, but are becoming very important in medicine. One of the methods white blood cells (WBC) use to kill bacteria is to enclose the bacteria in a membrane and then to inject oxygen radicals into the vacuole (WBCs make the O_2 radicals). The oxygen radicals actually kill the bacteria. In addition we now know that O_2 radicals are the final method of damage in many diseases. Oxygen radicals are therefore both 'good' and 'bad'.

It would seem reasonable to conclude that if O_2 radicals cause cellular damage, taking 'anti-oxidants' should help reduce the damage. So far, the results of many well-designed studies have failed to show any benefit from taking anti-oxidant supplements. Some benefit has been shown when increased amounts of anti-oxidants are consumed by eating foods high in anti-oxidants. This suggests that something else in the food is required to get the beneficial effect of the anti-oxidants that is not available in the supplements.

"The first and most basic point is that molecular O_2 is not toxic!"

The bottom line is that anytime O_2 exists, O_2 radicals will be formed. The number of O_2 radicals is proportional to the PO_2. All of our cells have defenses against the damage caused by O_2 radicals. At normal PO_2, our cells are more than capable of repairing the damage being caused by the O_2 radicals. As the PO_2, and the number of O_2 radicals is increased, a point is reached where the cells cannot repair the O_2 radical damage as quickly as it is occurring. Therefore, the damage will accumulate until the function of the cell is impaired or the cell dies.

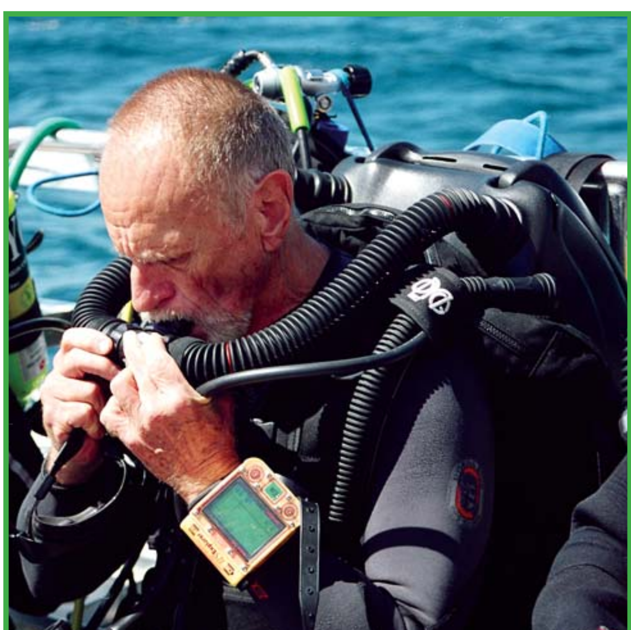


Photo Courtesy of OMG

Signs & Symptoms of O_2 Toxicity

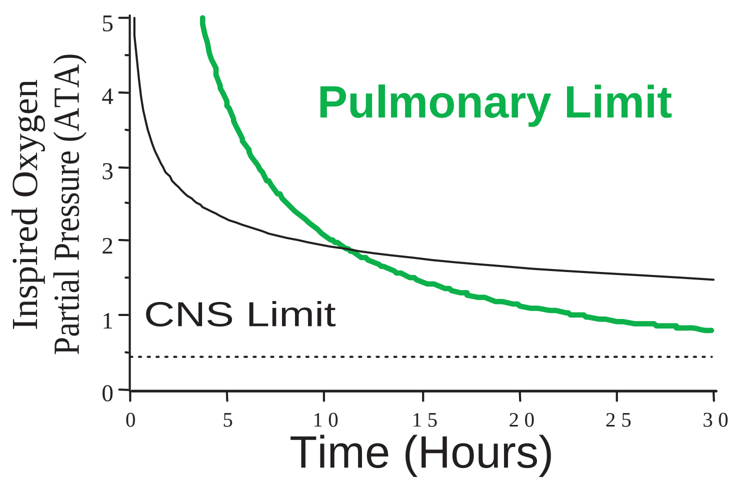
Given the above explanation, it should be obvious that the toxicity of O_2 will depend on the PO_2 and the time of exposure. The other factor is that we are all biologically different and some individuals will have more defenses against O_2 radicals than others. To further complicate the issue, our defenses against O_2 radicals also change greatly from day to day. Therefore, we have marked differences in sensitivity to O_2 radical damage in different people and on different days in the same person.

In general, the susceptibility of a cell to oxygen toxicity is related to its rate of metabolism in that a resting cell is relatively resistant. This makes sense in that O_2 radicals interfere with cell processes and the slower these processes are occurring; the longer it will take for the damage to make a difference. We also know that things that stimulate the cells, like caffeine, increase the risk of O_2 toxicity while things that slow down the cells have some protective effect.

Every cell in the body will eventually die if it is exposed to enough O_2 radicals. But in the intact person the lungs and the brain will suffer serious damage before the other tissues. The eyes can also suffer damage at relatively modest exposures.

The human body is able to tolerate increased levels of oxygen, up to about 0.45 ATA, without problem. At a PO_2 between 0.45 ATA and 1.6 ATA, the toxic effects are mainly on the lungs and take hours or days to develop. At pressures over 1.6 ATA, the toxic effects are mainly on the brain (CNS) and may develop in a few minutes.

The majority of recreational divers will not have to worry about oxygen toxicity because the PO_2 will never be high enough, for long enough, to cause problems. However, the rapidly rising use of Nitrox makes O_2 toxicity a problem that all divers should understand. As technical divers, and even more as CCR divers, a thorough understanding of O_2 toxicity is critical.



Graph of the predicated pulmonary and CNS toxicity limits of exposure to varying partial pressures of oxygen.

Data from Bennett and Elliott, The Physiology and Medicate of Diving, 4th Ed. pg.155, 1993

Dr. J. Lorrain Smith first described the toxic effect of oxygen on the lungs in 1899. He noted that the severity of the effect increased with increasing PO_2 and that the effects where largely reversible.

The earliest sign of pulmonary (lung) oxygen toxicity is a mild irritation in the trachea (throat) that is made worse with deep inspiration. A mild cough develops next, followed by more severe irritation and cough until inspiration becomes quite painful and the cough becomes uncontrollable. If exposure to oxygen is continued, the person will notice chest tightness, difficulty breathing, shortness of breath, and if exposure is continued long enough, the person will die, from lack of oxygen! The progressive damage to the lungs eventually makes it impossible for the oxygen to get to the blood as it passes through the lungs.

The time to onset of symptoms is highly variable but most individuals can tolerate 12-16 hours of oxygen at 1.0 ATA, 8-14 hours at 1.5 ATA, and 3-6 hours at 2.0 ATA before developing mild symptoms. There are several ways to track developing pulmonary oxygen toxicity but the most sensitive and accurate is the development of symptoms. A second technique is to monitor the vital capacity. Vital capacity (the amount of air that can be moved in one large breath) decreases with increasing pulmonary toxicity. A reduction of approximately 2% in vital capacity correlates with mild symptoms while a reduction of 10% correlates symptoms so severe that most individuals will not voluntarily continue breathing oxygen. These mild effects are completely reversible and no permanent lung damage occurs. However, the damage will take up to 12 days to heal. The pathology of pulmonary oxygen toxicity is understood but beyond the scope of this discussion.

A third way to keep track, in rough terms, of pulmonary oxygen toxicity is to keep track of the oxygen exposure. This technique is called calculating the Unit Pulmonary Toxic Dose or Oxygen Tolerance Unit (OTU), and one OTU is equivalent to breathing 100% oxygen, for one minute, at 1.0 ATA. As a guide, 615 OTUs in one day will cause a 2% reduction in vital capacity and 1,425 units will cause a 10% decrease. There are several different ways to calculate the OTU (some try to correct for increasing toxic effects with increasing dose, in addition to the simple PO_2) and there is quite wide variation in individual tolerance so that symptoms are still the best guide. The situation where OTUs are most useful is in planning a large number of dives, in a few days, all involving a large amount of oxygen decompression. Even then, the dive plan may have to be altered if the diver develops symptoms of pulmonary toxicity.

The first and most important method to prevent pulmonary oxygen toxicity is to limit exposure to the lowest possible PO_2 for the shortest period of time. If you dive only air and limit your depth to a maximum of 130 fsw (40 msw), pulmonary oxygen toxicity is unlikely to be a problem. The second method to prevent pulmonary oxygen toxicity is to provide air breaks. The damage to the cells is cumulative and if for every 25 minutes of oxygen exposure you provide the cells with a five-minute period where the diver breathes air, the diver can tolerate twice as much oxygen before toxic symptoms develop when air breaks are given compared to breathing oxygen continuously. Basically what happens is that during the air breaks the cells are repairing the damage due to O_2 radicals much faster than damage is occurring so they 'catch up' on some of the damage. Therefore, it will take much longer for a given level of damage to accumulate.

Oxygen toxicity in the brain (CNS) is a problem of higher PO_2s for shorter periods of time. While breathing air, a PO_2 of 1.6 ATA is not reached until a depth of 218 fsw (67 msw). Therefore, CNS oxygen toxicity is not a problem for standard recreational diving. However, more and more divers are using Nitrox and if you dive breathing a 40% oxygen mixture, the PO_2 will be 1.6 ATA at a depth of only 99 fsw (30 msw) and if you decompress on 100% oxygen, the PO_2 will be 1.6 ATA at a depth of 20 fsw (6 msw)! Therefore, CNS oxygen toxicity is a serious problem for some recreational divers, and a major problem for technical and commercial divers.

The first and most serious sign of CNS oxygen toxicity is often a grand-mal type convulsion. There are many other signs and symptoms of oxygen toxicity but there is no consistent warning that a seizure is about to occur. Even the EEG is completely normal until the convulsion starts. The convulsion due to oxygen toxicity is not believed to cause any permanent problems in and of itself because the body starts the convulsion with a surplus of oxygen on board and thus the hypoxia seen with normal seizures is not a problem. However, the diver who convulses while in the water may drown or, if they ascend while the glottis is closed, may suffer pulmonary barotrauma.

A short list of signs and symptoms of CNS O_2 toxicity

CON vulsion - grand mal seizure, usually without warning
V ision - tunnel vision or any other change
E ars - ringing in the ears or other changes
Nausea - mild to severe, continuous or intermittent
T witching - usually facial muscles, most frequent symptom
I rritability - behavior or personality changes
Dizziness - vertigo, disorientation

Notes:

There is huge variation in the amount of oxygen individuals can tolerate before they show signs of CNS oxygen toxicity and of even more concern, a huge variation in the same person on different days. A diver may do many dives in which they are exposed to a high PO_2 with no difficulties and falsely conclude that they are resistant to oxygen toxicity. Then, for no apparent reason, they may suffer a CNS hit on a dive where they are exposed to a lower PO_2. In general, people can tolerate more oxygen in a dry chamber than in the water. In fact, most divers can tolerate two hours of oxygen at 3.0 ATA (66 fsw/20 msw) in a chamber with few difficulties. While exercising in the water however, several divers have had convulsions at PO_2s as low as 1.6 ATA. To make matters worse, in the chamber divers often have one of the less serious signs of oxygen toxicity such as tunnel vision, ringing in the ears or twitching, whereas in the water the first sign is often a seizure. The seizure starts with an immediate

Photo by Warren Miller

loss of consciousness and a period of about 30 seconds when the muscles are relaxed. All of the muscles of the body then contract violently for about one minute. The diver then begins to breath rapidly and is very confused for several minutes afterwards. As you can well imagine, if this happens during a dive, the diver usually dies. The table gives a short list of the signs and symptoms of CNS oxygen toxicity but almost anything is possible.

There are some factors that are known to increase the risk of CNS oxygen toxicity. I have already mentioned two; submersion in water and working hard. The risk with working hard is that the PCO_2 in the body is increased. This increases the blood flow to the brain. Other causes of increased PCO_2 are skip breathing and increased CO_2 in the breathing gas. For the CCR diver, the primary cause of elevated CO_2 is scrubber failure. Increased stress on the diver and increased levels of adrenaline, atropine, aspirin, amphetamine and other stimulants all seem to increase the risk of CNS oxygen toxicity.

There are no drugs that can be used to prevent CNS oxygen toxicity. In animal experiments, the seizures could be prevented but the CNS cellular damage found after prolonged seizures still occurred. The only effective methods to prevent CNS oxygen toxicity are to limit PO_2, time of exposure, and give air breaks during oxygen breathing.

As general guidelines, the PO_2 during decompression at rest should never exceed 2.0 ATA and most divers use 100% oxygen at a maximum depth of 20 fsw (6 msw) 1.6 ATA. During the active part of the dive, the PO_2 should never exceed 1.6 ATA and many divers are using 1.5, 1.4, or even 1.3 as the maximum PO_2. NOAA, the US Navy, the Royal Navy, the Canadian Forces, and IANTD have guidelines for acceptable PO_2 and the maximum time that may be spent at each.

National Oceanic And Atmospheric Administrationoxygen Partial Pressure & Exposure Time Limits For Nitrogen/Oxygen Gas Divers

ATA	Single Exposure		24 Hour Maximum	
	Minutes	Hours	Minutes	Hours
1.6	45	0.75	150	2.50
1.5	120	2.00	180	3.00
1.4	150	2.50	180	3.00
1.3	180	3.00	210	3.50
1.2	210	3.50	240	4.00
1.1	240	4.00	270	4.50
1.0	300	5.00	300	5.00
0.9	360	6.00	360	6.00
0.8	450	7.50	450	7.50
0.7	570	9.50	570	9.50
0.6	720	12.00	720	12.00

Hyperoxic Induced Myopia

We have been discussing the effects of O_2 toxicity on the brain and the lungs and until fairly recently, that would have been the end of the discussion on O_2 toxicity in diving. However, with the rapid increase in popularity of diving rebreathers, and with the phenomenal bottom times possible when diving on a CCR, another problem has started to appear.

It has been known for years that if you do daily hyperbaric oxygen treatments in a chamber, over several weeks some people gradually develop progressive myopia (nearsightedness). The rate of onset is approximately one diopter per month and the rate of recovery after the treatments are stopped is approximately the same. In most people their vision returns pretty much to its' pre-treatment level.

Several CCR divers have noted a similar problem after a series of prolonged CCR dives. One 47-year-old CCR diver developed the problem after doing 47 dives in 12 days with a PO_2 of 1.3 ATA. The nearsightedness developed near the end of the trip and completely recovered over the next two months. He then did 16 dives over 11 days and the problem returned. Again, he recovered over about two months. Based on these and other case histories, it seemed that you needed to do at least 45 hours of diving in 12 days or less, and in general the problem did not occur before age 40.

In 2003, one of my students developed the problem after approximately 30 hours of dive time in 11 days with a PO_2 of 1.3 ATA. She was in her early 40s and fully recovered in a few weeks. Her problem was very mild but it developed with far less exposure than previously noted. A few divers have noted a hyperopic change (far sighted).

Not much is known about this problem. It seems to involve a stiffening of the lens and there is definitely a difference between people in their susceptibility to this problem. It does not seem to cause any permanent damage, but once you have experienced the problem, you seem to be more likely to have the problem in the future, with less provocation. The only treatment is to avoid an elevated PO_2, and the only way to prevent the problem is to also avoid an elevated PO_2.

So what does this mean for the CCR diver? First, it is yet another reason to be conservative with your O_2 exposures. If you are going to be doing a 'lot' of diving in a short period of time, it makes sense to reduce the set point to 1.2, 1.1 or even 1.0 ATA. You will need to do a bit more decompression, but the risk of O_2 toxicity will be greatly reduced. Finally, if you notice your vision has degraded near the end of an intense CCR dive trip, and if it recovers over the next several weeks of not diving, you most likely have experienced the problem and you will need to reduce your PO_2 for future diving.

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Chapter 3 - CO_2 & The Diver

by David Sawatzky, M.D.

Excess carbon dioxide CO_2 is one of the most complex, subtle, insidious, and potentially fatal problems a rebreather diver can face. Carbon dioxide elevation on the surface causes a fairly predictable series of signs and symptoms. There is some evidence to suggest that this nice progression does not necessarily happen when diving a rebreather, perhaps because of the elevated partial pressure of oxygen PO_2. Under these conditions, the first sign or symptom of elevated CO_2 can be loss of consciousness. In this chapter I will review the basic physiology of CO_2 and examine in some detail the problems a rebreather diver can face.

Carbon dioxide is present in the atmosphere in very small concentrations (0.03% or 0.23 mm Hg). Humans (animals and most O_2 using species) produce CO_2 by the metabolism of the fats, proteins and carbohydrates that they eat. Carbohydrates are composed of carbon, hydrogen and oxygen. When the body metabolizes them, one molecule of CO_2 is produced for every molecule of O_2 used (e.g. $C_6H_{12}O_6 + 6O_2 = 6\ CO_2 + 6\ H_2O$ + energy). Proteins and fats contain other molecules (e.g. nitrogen) and when they are metabolized, some O2 is required in the chemical reactions that handle these other molecules but no CO_2 is produced from these reactions. Therefore, when fats and proteins are metabolized, the amount of CO_2 produced is 70-80% of the amount of O_2 used.

It is impossible to know exactly what the overall ratio is in a diver because it not only depends on the type of food we eat, but the type of food that is being used to produce energy in our bodies. What food types are being used depends on the intensity and duration of the exercise, the fitness level of the diver, and many other factors. On the surface, on average, approximately 800 ml of CO_2 is produced for every 1,000 ml of O_2 used. However, for a rebreather diver it is reasonable to assume that the amount of CO_2 produced is the same as the amount of O_2 consumed by the body as you will only slightly over estimate the amount of CO_2 produced (the direction of the error increases the safety of the diver). Nature is always a balanced system. To complete the loop we need to remember that the CO_2 produced by animals, plants use. Plants produce O_2 as an end product.

It is important to remember that the amount of O_2 used when diving CCR is the amount used by the body, plus the amount wasted by the diver. Every time the diver ascends and vents gas and every time they clear their mask they are 'wasting' O_2. Calibrating and venting the loop also uses O_2.

Carbon Dioxide Physiology

The human body is designed to maintain the PCO_2 in arterial blood at 40 mm Hg (the PCO_2 of mixed venous blood is around 46 mm Hg). The alveolar PCO_2 is therefore also 40 mm Hg but when alveolar gas is mixed with gas from the dead space, PCO_2 in mixed expired air is approximately 32 mm Hg. However, if only the last bit of air exhaled (presumably all from alveoli) is measured, the PCO_2 will be very close to the arterial value. These values are the result of our metabolism and therefore, they do not change with depth.

Under normal conditions, each 100 ml of blood contains, 3 ml of CO_2 dissolved in the plasma (ten times the amount of dissolved O_2), 3 ml attached to hemoglobin and other plasma proteins (approximately 18 ml of O_2 is attached to hemoglobin), and 44 ml carried as bicarbonate (HCO_3-). At rest in a 70 kg male, approximately 200 ml of CO_2 are produced each minute. At maximum work however, over 3,000 ml of CO_2 can be produced per minute and a fit person can maintain work rates that produce over 2,000 ml of CO_2 per minute for more than 30 minutes.

Larger people obviously produce more CO_2 and in general, fitter people produce less CO_2 than unfit people at the same work rate. However, fit people can attain a much higher work rate and can maintain a high work rate for much longer than unfit people. This is very relevant to the CCR diver when the duration of the CO_2 absorbent canister is considered. For example, the Inspiration CCR canister is rated at 3 hours duration in 5C water with the diver producing 1,600 ml of CO_2 per minute, using 8-12 grade absorbent. From the previous information it can be seen that a hard working, fit or large diver can produce CO_2 at a higher rate, and therefore the absorbent canister will fail in less than 3 hours under these conditions.

How much we breathe is controlled by several factors including the PO_2 in arterial blood, the pH of the blood, stretch receptors in the lungs and chest wall, and the PCO_2 in arterial blood. Of all these factors, the partial pressure of carbon dioxide is by far the most powerful stimulus to respiration. When we increase production of CO_2 by exercising, the body quickly responds by increasing respiration so that arterial PCO_2 is maintained very close to 40 mm Hg (usually within 3 mm Hg). This mechanism is controlled by CO_2 receptors in the medulla of the brain. The peripheral chemoreceptors (carotid and aortic bodies) primarily respond to levels of oxygen in the blood and to the pH.

We can voluntarily over-ride these reflexes and breathe more or less than our bodies actually require, but only for short periods of time, and only to a limited degree. When we hold our breath, the PCO_2 rises in our blood as the cells continue to use $_{O2}$ and to generate CO_2. As the arterial PCO_2 rises, we have to resist a stronger and stronger drive to breathe until finally we are forced to take a breath, usually when the arterial PCO_2 rises to around 50 mm Hg.

Hyperventilation or Hypocapnia

When we hyperventilate (over breathe) we remove excess CO_2 from the body and the arterial PCO_2 falls. If we were to then hold our breath, it would take longer for the arterial PCO_2 to rise back to 50mm Hg where we would be forced to take a breath. The only problem is that if we hold our breath too long, our bodies will use up too much O_2 and we will pass out before we are forced to breathe. Many people die every year by hyperventilating and then seeing how long they can hold their breath or see how far they can swim underwater. They pass out and drown before their arterial PCO_2 rises to 50 mm Hg and forces them to surface to breathe.

Hyperventilation also causes other problems that divers should be aware of. As the CO_2 is removed from the body, the pH of the blood changes. This typically causes a tingling sensation of the hands, feet and around the mouth. If the person continues to hyperventilate, they can experience muscle spasms, become very light headed and pass out. How is this possible?

Carbon dioxide controls not only respiration, but it also controls the blood flow to our brains. The brain is unusual in that of all the tissues in the body, it and the heart are most sensitive to a lack of O_2. When we hold our breath and the PCO_2 rises, the blood flow to the brain increases and recent measurements have shown that the PO_2 in the brain does not change! When we hyperventilate however, the lower PCO_2 results in a dramatically reduced blood flow to the brain (hyperventilation does NOT increase the amount of O_2 carried by the blood, nor the amount of O_2 in the body). The blood flow to the brain becomes so small that the brain cells use more O_2 than the blood can deliver and they become hypoxic. If the person continues to hyperventilate, they will loss consciousness due to hypoxia of the brain.

Hyperventilation is quite common and is usually associated with stress or anxiety. When a diver faces

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an emergency, or simply a difficult situation, the natural tendency is to hyperventilate. An open circuit diver risks running out of gas. While the rebreather diver will not run out of gas, they still risk all the nasty side effects of lower CO_2. Therefore, the recommendation to stop, take three slow, deep breaths when faced with any problem or emergency situation is valid for both OC and rebreather divers (assuming the problem is not lack of breathable gas!)

Acute Hypercapnia

There are two ways in which the PCO_2 in the body can be increased. Either the CO_2 in the inspired gas is elevated or we fail to completely eliminate the CO_2 produced in the body, thereby allowing it to accumulate. Both mechanisms can be a problem in divers.

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"Excess carbon dioxide (CO_2) is one of the most complex, subtle, insidious, and potentially fatal problems a rebreather diver can face."

In open circuit (OC) diving (standard scuba), the only way to increase the inspired CO_2 is by contamination of the breathing gas. This most commonly will occur if the intake from the compressor is too close to the exhaust of an internal combustion (gas, diesel, propane, etc.) engine (you also get CO). In rebreather diving the most common problem is failure of the absorbent system. Most commonly this occurs when the diver forgets to change the CO_2 absorbing material but it can also happen if the material is not inserted correctly (channeling), if the material is contaminated with seawater, if the material has too large a granule size or if the material does not absorb CO_2 properly. In addition, there can be problems with the design of the rebreather. Finally, the ability of the material to absorb CO_2 is variable depending on the temperature. It is less effective if you are diving in cold water than warm water. When diving a full-face mask, helmet or diving in a chamber, CO_2 can become elevated if the ventilation rates of the gas space are too low. These problems are all relatively easy to avoid.

The second mechanism of elevated CO_2 is when the diver fails to completely eliminate all of the CO_2 produced in his body. There are several ways in which this can occur. First, if the diver is anxious, they might breathe very rapidly, but take only very small breaths. The first few hundred ml that we inhale simply move the old gas that was sitting in the regulator, mouth and airways into the alveoli. If we are taking only shallow breaths, we will be moving no new gas into the alveoli but simply moving the same gas back and forth, thereby stopping the elimination of CO_2 and the delivery of O_2 to the body. Whenever you have a problem breathing, diving or not, it is important to take slow deep breaths to ensure you are moving the maximum amount of fresh gas in and out of the alveoli.

A second way in which CO_2 can accumulate in the body is if the person does not have a normal increase in respiration with increased CO_2 production. Most people maintain arterial PCO_2 at 40mm Hg by increasing respiration, even with heavy exercise and large increases in CO_2 production. Some individuals do not. They allow the arterial PCO_2 to increase, sometimes as high as 70 mm Hg! These individuals are called CO_2 retainers and there seem to be more CO_2 retainers amongst divers than in the general population. There are several theories for this. First, when breath-hold diving was a prerequisite for scuba diving, CO_2 retainers would have been selected because they could hold their breath longer. Second, in some forms of diving (hard hat and old pendulum type rebreathers) the diver was chronically exposed to elevated CO_2 in the inspired gas. Third, some divers chronically hypoventilate to try and use less gas, resulting in elevated levels of PCO_2 in their bodies. It is theorized that these divers adapt and learn to tolerate higher levels of CO_2. Unfortunately, some individuals retain CO_2 even though they have never been chronically exposed to elevated CO_2 levels. The only sure way to identify these individuals is to measure their CO_2 in a lab while they are diving or exercising. Warning signs however include divers who use very little gas and those who

Photo by Tom Mount

often end dives with a headache. These individuals are at risk for CO_2 problems.

A third way that CO_2 can accumulate in the body is if the work of breathing is increased. The body maintains a balance between the arterial PCO_2 and the work of breathing. If breathing is made more difficult, a higher level of arterial PCO_2 is necessary to generate the required 'drive' for the increased work of breathing. There are many reasons why the work of breathing increases. First, all regulators and breathing loops have some resistance, some more than others. Second, all gases become denser as pressure increases. This increased density makes it harder to move the gas through the regulator/breathing loop and the lungs. Most regulators are OK at shallow depths but many become difficult to breathe through as the gas density increases with depth. My old Sherwood Blizzards are great for shallow dives but not recommended deeper than 100 fsw / 30 msw). The largest problem is increased work of inspiration. The inspiratory muscles are very small and fatigue easily if worked too hard. Conversely, we can generate large expiratory pressures (blowing up balloons) by using some of the larger muscles in the body. Third, tight wet suits, dry suits, harnesses, buoyancy compensators, etc. all interfere with movement of the chest wall and thereby increase the work of breathing.

Photo by Tom Mount

When diving at shallow depths with standard scuba gear, most divers will have an increased PCO_2 if they exercise at more than 60% of their maximum. At deeper depths, this will occur at lower work levels because of the increased gas density and increased work of breathing. Rebreathers all have potential problems with the work of breathing because of the flow resistance caused by the one-way valves, counter lungs, water traps, CO_2 absorbent, etc. Work of breathing (WOB) must be measured in any rebreather and it must meet a reasonable standard. The Inspiration CCR meets the new European Union standards (even lower than the old standards). Some other rebreathers have not even been tested!

Signs & Symptoms of Hypercapnia

Most research has been done on resting subjects at sea level pressure. Under these conditions, the onset of signs and symptoms as the PCO_2 is increased are well known and quite consistent. At 3% CO_2 in air (22 mm Hg), respiratory minute volume is doubled but there are no CNS changes. At 5 or 6% CO_2 in air (40-45 mm Hg), respiration continues to increase and the person will usually be anxious, short of breath, blood pressure and pulse rate will be increased. Mental confusion and lack of coordination may become apparent. At 10% CO_2 in air (76 mm Hg), there is severe mental impairment with a drop in BP and pulse rate. At 12% CO_2 in air, the person may loose consciousness. Remember that these signs and symptoms are in the resting subject, on the surface, breathing 21% oxygen.

Another study showed the following sequence of signs and symptoms as the inspired PCO_2 was slowly increased. Increased respiration, dizziness, unsteadiness, disorientation, restlessness, sweating of the forehead and hands, flushed face, muscular fasciculation, lack of coordination, ataxia, jerking movements of the limbs, confusion, gross tremor, convulsions, loss of consciousness. When the person is placed back breathing room air, the signs and symptoms rapidly clear, except that they may suffer from a throbbing bitemporal headache (that does not respond to drugs), nausea, and malaise for several hours.

These studies have caused us to believe that a slow rise in PCO_2 (as might be expected when the scrubber starts to fail in a rebreather) should result is a slow progression of signs and symptoms so that the diver has lots of time to identify the problem and take corrective action before the signs and symptoms become serious or life threatening. Unfortunately, this does not appear to always be true. In addition, the rise in PCO_2 when the scrubber fails in a rebreather is often quite rapid.

The diver is usually distracted by other things and may not notice the increased respiration (especially if they are working fairly hard). In the water, the diver will not notice if they are sweating. Dizziness, unsteadiness, etc. will be far less noticeable. Therefore,

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the diver might go through all of the mild signs and symptoms of rising PCO_2 and not notice them. When the more serious symptoms occur, the diver is often unable to take corrective action. One reference stated that for SCR rebreathers, elevated PCO_2 is the most common cause of loss of consciousness (for CCR it is hypoxia).

There are even more problems. If the rise in PCO_2 is rapid, the first sign or symptom is sometimes loss of consciousness (acute exposure to 20-30% CO_2 causes convulsions in 1 to 3 minutes, a single breath can cause mental incapacitation).

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On the surface, the increase in respiration is essentially linear between 4 and 10% CO_2 in inspired air. However, if the PO_2 is elevated (as it always is when diving) the respiratory response to increasing PCO_2 can be blunted. One reference suggested that this was especially true when the diver was working above his anaerobic threshold. This is usually between 70 and 80% of the person's maximum work capacity on the surface but it will be less at depth. Another reference suggested that this only happens in some divers. Therefore, if the diver is working fairly hard, they will probably not notice the increase in respiration as the PCO_2 starts to rise. In this case, the first symptom may be paranoia, severe anxiety, panic, or loss of consciousness.

It should now be apparent that the diver at most risk of developing hypercapnia will be diving deep (increased gas density and work of breathing), working hard (high CO_2 production) and/or breathing a high PO_2 (failure of the normal respiratory response to rising PCO_2, therefore few warning signs before LOC). Young, inexperienced, highly motivated divers on shallow oxygen rebreathers are quite likely to loose consciousness from elevated PCO_2. In these divers (those who survive), 50% will not remember any warning signs or symptoms before they lost consciousness.

Elevated PCO_2 also causes other problems. Carbon dioxide is narcotic and has an additive effect with nitrogen. Therefore, it will make nitrogen narcosis worse.

Carbon-dioxide levels are the primary controller of blood flow to the brain. From 4 to 10% CO_2 in air, the increase in CNS blood flow is linear as the PCO_2 rises. Therefore, if the diver is breathing an elevated PO_2 as well as having an elevated PCO_2, much more O_2 will be delivered to the brain. These divers are at greatly increased risk of experiencing an oxygen convulsion, at PO_2s that would otherwise be safe.

Avoiding CO_2 Problems

The first step is to ensure there is no CO_2 in the gas that is compressed into the tanks in your rebreather, or stage/safety bottles. The oxygen bottle is seldom a problem, but the diluent bottle is usually filled from a standard air compressor so all of the open circuit CO_2 considerations apply (a well functioning and maintained compressor with the air intake remote from any potential sources of CO_2).

The second step is to ensure that your rebreather is working properly (no leaks, etc.) to ensure the minimum breathing resistance on the loop.

The third step, and the area most rebreather divers get into trouble, is the scrubber. You must use sodasorb/sofnolime that has been designed for diving. The material used in hospitals (anesthetic machines) tends to have too low a moisture content, and to be too soft (breaks up to form dust) for safe use in diving. The granule size determines the surface area of the material. Larger granules mean less surface area and therefore less CO_2 will be absorbed. As a rough rule of thumb, 8-12 grade material will last 50% longer than 4-8 grade material (three hours for 8-12 vs. two hours for 4-8 grade on the Inspiration). The scrubber material must be kept sealed. If the scrubber material has been exposed to air for too long (days) it will absorb CO_2 from the air and be 'used up' or at least partially used up when you put it in your rebreather. In general, the same amount of scrubber material will absorb the same amount of CO_2, no matter which rebreather it is placed in. When different manufacturers claim widely different durations for scrubbers that hold the same amount of material, be suspicious of the liberal claims.

Change your absorbent frequently. It will cost you a bit more, but then, *"What is your life worth?"*

The next step is to ensure that the material is packed evenly. If packing is uneven, gas will preferentially travel through the loosely packed material. That material will quickly be saturated with CO_2 and CO_2 will start to pass through the scrubber. Even packing ensures that all of the material is used to absorb CO_2.

It is vital to keep careful track of the time you have used the scrubber and to change the absorbent when required. Pay particular attention to your size, fitness level, and work rate to ensure you change the absorbent material before the manufacturer's recommended time if required. Cold water will cause the scrubber to fail sooner and on deeper dives you must have fresh scrubber material. Detailed explanations for these guidelines can be found in the chapter on scrubbers.

The ultimate solution might be to have a CO_2 monitor as part of the rebreather, but there are several problems with this approach as well. First, all currently available monitors are either very expensive and/or not reliable in the dive environment. Second, if a scrubber starts to break through at depth, there is very little time before the PCO_2 rises to dangerous levels. Third, all closed circuit rebreathers have O_2 monitors, and usually audible alarms. Divers still ignore them and die!

The last step in reducing the likelihood of CO_2 problems is the pre-dive pre-breath. It is very tempting to skip this step but it is very important. Sodasorb/sofnolime needs water vapor and heat to work properly. When you first start to breath on the rebreather, the scrubber is not working at full efficiency. Over the first few minutes the moisture content in the absorbent goes up (the gas you exhale is 100% saturated by your body, and water is produced as the scrubber absorbs CO_2), and the temperature of the scrubber rises (as CO_2 is absorbed, heat is produced). In addition, if there is a problem with the scrubber (expired absorbent or your forgot to fill it!), or a problem with the oxygen supply (tank turned off, empty, etc.) it is far better to find out while you are sitting on the boat than when you are on your way down and negatively buoyant. If you lose consciousness sitting on the boat, you will most likely survive. If you pass out while negatively buoyant during descent, you will most likely die.

Conclusion

Carbon dioxide is a serious problem for rebreather divers. Elevated CO_2 will dramatically increase the level of nitrogen narcosis, and increase the risk of oxygen toxicity at otherwise safe PO_2 levels. The signs and symptoms of rising PCO_2 are unreliable while diving a rebreather and in up to 50% of divers, the first sign or symptom is loss of consciousness. In many

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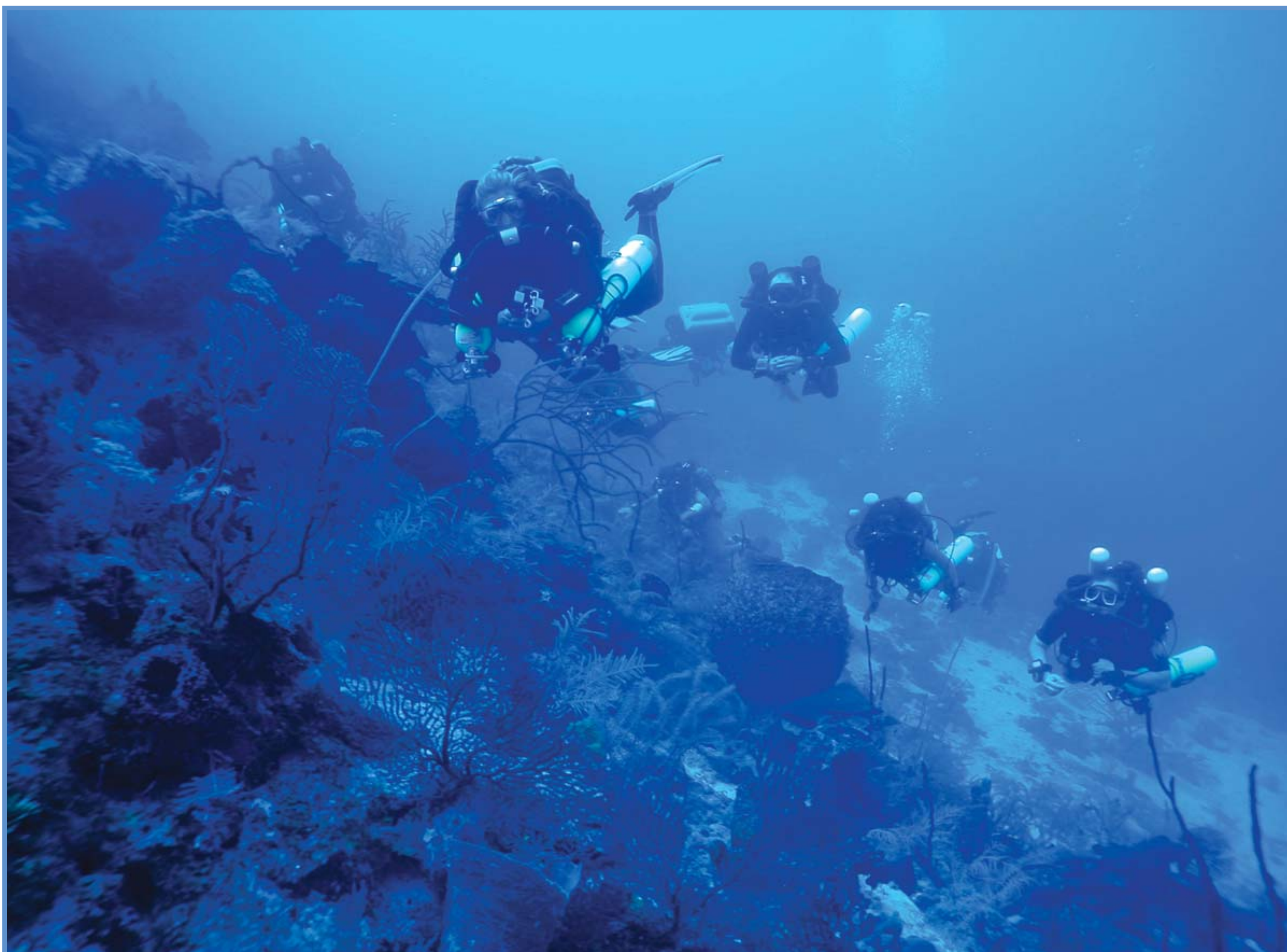
other divers, the first sign or symptoms is so serious that they are unable to appropriately respond to the situation (psychosis, inability to think clearly, etc.). The more rapid the rise in PCO_2, the more likely the diver will not notice and respond to the problem in time. Therefore, it is vital that you limit your activity while diving a rebreather to limit the amount of CO_2 your body is producing. This is even more important when diving deep. The increased gas density makes respiration a problem, even a relatively light work rates. If you are not working hard, even if the scrubber fails, the rise is PCO_2 will be relatively slow and you will most likely be able to recognize the problem and respond appropriately (go OC). The bottom line is change your absorbent frequently. It will cost you a bit more, but then, ***"What is your life worth?"***

Photo by Tom Mount



Chapter 4 - CO_2 Absorption

by Joerg Hess, M.S.

The introduction of rebreathers as life support systems was dependent upon the development of means to eliminate Carbon Dioxide (CO_2). The original solutions were rudimentary, but performed sometimes better than desired, resulting in excessive heat production. Empirical research led to modern absorbent materials and designs. Today, different solutions are available for different tasks. These range from life support systems in space travel, over diving systems to fire fighting and mine rescue. They all share the same design concept, and basic components.

CO_2 absorption is easily outlined; simply insert the right chemical equations into the standard process engineering approach. The purpose of a CO_2 absorption canister is that it removes CO_2. It is a machine that performs its job, until it runs out of power. That is pretty much all there is to know. The real absorption canister is still seen as a black box. The exact details of how the absorption canister behaves under varying conditions throughout the dive remain uncertain. Ongoing discussions between experts in the various fields of physiology, chemistry, and rebreather application and design reveal the complex nature of understanding exactly what is happening inside the "scrubber." Many ideas are expressed, but usually lack a solid explanation or even proof. Research projects have been done to clarify the absorption process by means of empirical measurements. It was hoped to gain a better understanding of the absorption behavior and to develop a sensory system to indicate the CO_2 content of the breathing gas. These attempts did not lead to the desired results. Whenever simple "trial and error" does not result in a conclusion, it is time to step back and look at the theory.

This chapter is to provide a basic understanding of the capabilities and limitations of a chemical CO_2 absorption system for rebreathers. It does not claim to be complete. It also only provides a very limited perspective – there is more to know, and much more still to find out.

Before taking off into the depth of rebreather absorption theory, some basic concepts have to be refreshed.

Adsorption Vs. Absorption

Although rather academic in discussion, a little clarification seems appropriate at this point. The reduction of CO_2 inside today's conventional semi-closed or closed circuit, self-contained underwater breathing system depends on various reactions and processes. While the chemical parts of the removal are depending on catalytic reactions to a great extend, it is nevertheless not possible without chemical reactions. In an adsorption by catalysis, the desired result is achieved while leaving the reaction aids unchanged. In absorption, a chemical reaction will change all components involved.

To put it into plain English, since the absorbent itself is used up, we are dealing with a chemical absorption.

Surface Equivalent Value (SEV)

Historically, measurements are preformed in a laboratory on the surface, at an ambient pressure of approximately 1ATA. Any results are provided in percent, because that is a convenient way to present the data, and allow easy conversion into absolute values. Physiology, and Physics, and Chemistry however seldom function in percent. When dealing with gases, they mostly function with partial pressure. The concept of "surface equivalent value (SEV)" allows for the transition between the historic way and the "new" hyperbaric environment.

In our case of CO_2 absorption, the US NAVY defines a break through at the point when CO_2 from the canister exceeds 0.5% SEV (Curley 2001 and NEDU Technical Manual NO. 01-94). Although seemingly a percentage, this is an equivalent to the partial pressure of CO_2 when it is present with 0.5% on the surface. It equals 0.005 bar partial pressure. This partial pressure is constant. The percentage is not!

Partial Pressure

Before confusion about the last statement takes over, the concept of partial pressure needs to be reviewed.

Although we are not living in an ideal world, many processes can be simplified as ideal with a reasonably small error. For diving purposes, the gas we are breathing is usually assumed to be an ideal gas, following the ideal gas equation:

$$P\ V = n\ R_m\ T$$

P	Partial Pressure
V	Volume
n	Amount
R_m	Gas constant
T	Absolute Temperature

Please note that the amount means "number of molecules."

If volume and temperature are maintained constant, partial pressure is a synonym for amount. The human body maintains a constant temperature, and the tidal lung volume remains constant while diving on scuba. The assumption of partial pressure relating to amount is therefore reasonable, resulting in:

$$P = n \text{ X constant}$$

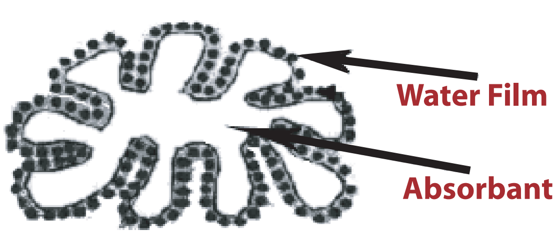
The body consumes an amount of oxygen molecules to support life functions. It then produces about the same amount of CO_2 as a result. The amount of consumed oxygen only depends on physical stress, not on ambient pressure. The partial pressure (amount) of CO_2 exhaled is therefore independent of depth, too. droplets hit either side of the optics, measurements are inaccurate.

CO_2 Absorbents

Several groups of scrubbing materials are classified (Wang, 1982): Alkali metal hydroxides, alkali metal superoxides and peroxides, and other methods such as molecular sieves, membrane separation, freeze-out, and photosynthetic gas exchange.

The first recorded chemical CO_2 absorbent canister, "scrubber," was used by Henry Fleuss in 1879 to absorb CO_2 in his O_2 rebreather. The scrubbing material consisted of rope yarn soaked in solution of caustic potash [KOH] (Clarke, 99, pp 466).

Absorbent Granule



Today's chemical absorbents consist of small pellets of varying diameter, spheres, half spheres or granules.

Alkali Metal Hydroxides

For short duration operations, alkali metal hydroxides are the most attractive material to control CO_2.

Lithium Hydroxide

Anhydrous lithium hydroxide [LiOH] is a very effective CO_2 absorbent used in submarine and space applications. However, because of its high toxicity, it has been used only in experimental diving applications where gas permeable but water-repellent cloth (Versapel) can keep the absorbent dry. Unlike sodalime, LiOH maintains absorption efficiency at temperatures near 0°C. (Clarke, 1999, p. 467).

The reaction takes place in two steps: reversible adsorption of water vapor followed by irreversible chemical reaction with CO_2.

$$LiOH + H_2O \Leftrightarrow LiOH\ H_2O$$

$$2\ LiOH\ H_2O + CO_2 \Leftrightarrow Li_2CO_3 + 3\ H_2O$$

Chemical Reaction of Lithium Hydroxide

The first widely used CO_2 absorbents for commercial and military diving consisted of pellets of sodium hydroxide [NaOH], commercially termed *Shell Natron*. Sodium hydroxide is a white crystalline substance that readily absorbs CO_2 and moisture from air, with release of water and heat. It is very soluble in water carbonate (Columbia encyclopedia, 2001). Unfortunately, under certain unusual circumstances, the caustic mixture of NaOH and water can be accidentally inspired, with catastrophic consequences. For that reason, modern absorbents for diving applications use various less caustic hydroxide mixtures to improve safety (Clarke, 1999, p.466).

Soda Lime

One of the first such mixtures was *Baralyme*, which eliminated NaOH altogether. *Baralyme* consists of hydrated lime (calcium hydroxide), with potassium hydroxide [KOH] added as a chemical activator. Baralyme contains 74% $Ca(OH)_2$, 11% $Ba(OH)_2$, 5% KOH, and 10% H_2O. More recently, its absorbent efficiency was improved by replacing $Ba(OH)_2$ with a small amount of NaOH in sodalimes such as *Sodasorb* and *Sofnolime*. Calcium hydroxide is a colorless crystal or white powder. It is a strong base. It is used in white ash, mortar, and plaster. It is only slightly soluble in water, about 0,2 grams per 100 cubic centimeters, so its solutions are weakly basic. Calcium hydroxide readily reacts with CO_2 to form calcium carbonate (Columbia Encyclopedia, 2001).

Typical diving grade soda lime absorbent consists of less than 4% sodium hydroxide [NaOH] (Dräger p.104), less than 1% potassium hydroxide [KOH], approx. 80% calcium hydroxide [$Ca(OH)_2$] and less than 1% silica as binding agent. Some manufacturers include additives to cause a color change with usage (Mount et al., p.47). The product typically contains 14 to 18% of water before use (Clarke, 1999, p. 467). Soda lime usually consists of white granules at room temperature and it is said to absorb 25 to 35% of its weight in CO_2. The basic reactions include:

$$CO_2 + H_2O \Leftrightarrow H_2CO_3$$
$$Ca(OH)_2 + H_2CO_3 \Leftrightarrow CaCO_3 + 2H_2O$$
$$NaOH + H_2CO_3 \Leftrightarrow NaHCO_3 + H_2O$$

Chemical Reaction of Soda Lime

If given enough time, sodium hydroxide will react with calcium, reducing it back to calcium hydroxide:

$$2NaOH + CaCO_3 \Leftrightarrow Na_2CO_3 + Ca(OH)_2$$
$$Na_2CO_3 + CO_2 + H_2O \Leftrightarrow NaHCO_3$$

Chemical Reaction of
Sodium Hydroxide with Soda Lime

Furthermore, calcium carbonate will slowly react with carbonic acid:

$$CaCO_3 + H_2CO_3 \Leftrightarrow Ca(HCO_3)_2$$

Chemical Reaction of
Calcium Carbonite with Carbonic Acid

Delayed by diffusion, the results of the later reactions can be found after a day of leaving the partially used CO_2 scrubber by itself. The activator of the overall reaction is then used up. In cold water, soda lime itself will not produce enough heat to achieve a self-contained reaction. The use of a freshly filled rebreather canister should therefore be restricted to a time frame of 24 hours.

Alkali Metal Superoxides & Peroxides

Alkali superoxides or peroxides simultaneously remove CO_2 and generate O_2.

Potassium superoxides, KO_2, formed by spontaneous oxidation of potassium, would at first glance seem to be an ideal CO_2 absorbent; it reacts with CO_2 and water to yield bicarbonate and oxygen, as follows:

$$4\ KO2 + 4\ CO_2 + 2\ H_2O \Leftrightarrow 4\ KHCO_3 + 3\ O_2$$
or
$$4\ KO_2 + 2\ CO_2 \Leftrightarrow 2\ K_2CO_3 + 3\ O_2$$

Chemical Reaction of Potassium Superoxides

Another alkaline metal superoxide reacts thus:

$$4\ NaO_2 + 2\ CO_2 + 2\ H_2O \Leftrightarrow 4\ NaHCO_3 + 3\ O_2$$
or
$$4\ NaO_2 + 2\ CO_2 \Leftrightarrow 2\ Na_2CO_3 + 3\ O_2$$

Chemical Reaction of Alkaline Metal Superoxid

In the process of absorbing CO_2 and moisture, both superoxides release O_2. On a molar basis, however, sodium superoxide is not as efficient at removing CO_2 and producing O_2 as the potassium superoxide. Unfortunately, the amount of released O_2 depends on the extent to which water participates in the reaction. The anhydrous reactions tend to produce a surplus of O_2 relative to the CO_2 absorbed, whereas the hydration reactions do not.

The major drawback to both of these reactions is that they are very exothermic, capable of producing dangerously high-inspired gas temperatures. An excess of water can yield a violent reaction, releasing noxious fumes. For that reason, the superoxides are typically used only in dry-land applications: for example, in mine safety equipment or some firefighter's breathing apparatus (Clarke, 1999, p 466).

Miscellaneous Methods

Molecular Sieves

Molecular sieves absorbents were introduced to the industry in 1954. They have been applied by the process industries to the drying and purification of a large variety of gas and liquid streams. Molecular sieve absorbents are synthetic crystalline zeolites. They have a relatively high affinity for CO_2, but a still higher affinity for water. Thus, water will be picked up in preference to CO_2, displacing CO_2 previously absorbed (Wang, 1982). They therefore are not applied in self-contained diving.

Membrane Separation

Membrane separations are receiving active attention. The power and area requirements still appear excessive. But in combination with other methods, this single-phase operation looks promising.

Freeze-Out

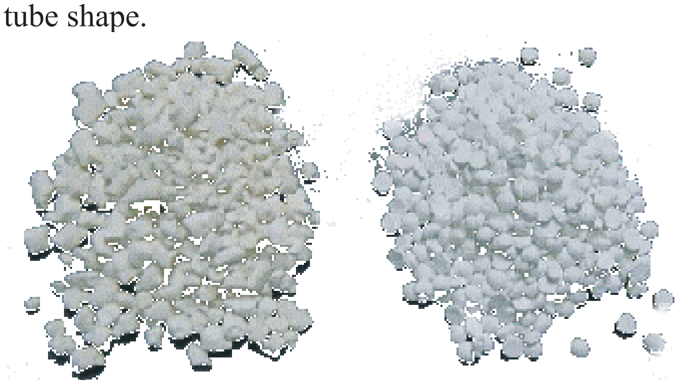
The most attractive freeze-out system is one in which both the water entrained by the process gas and the CO_2 are removed by freezing, subsequently, the solids are sublimated to vacuum and the heat of sublimation recovered in a regenerative manner to cool the incoming gas. The disadvantage of this method is the complicated process.

Photosynthetic Gas Exchange

Algae cells (green plants) use light energy to convert CO_2 and water into oxygen and organic compounds required for the formation of new cell material. The possibility of a compact, efficient algal system is still remote (Wang 1982).

Existing Absorbent

Most commonly used absorbents in rebreather diving consist of small pellets, of either spherical or tube shape.



Dräger Divesorb

Dräger produces CO_2 absorbent material for several purposes. Divesorb consists of half spheres of about 2mm radius. The following technical data is taken from Dräeger's Divesorb data sheet:

Molecular Products Sofnolime

Molecular Products produces CO_2 absorbent material for several purposes. Sofnolime consists of cylinders of different sizes. The following technical data is taken from Molecular's Sofnolime data sheet:

Composition	Calcium Hydroxide, Alkali Phosphate, Water
Shape	Hemispherical Pellets
Color	White
Size	
Tyler Mesh	5 – 9 mm
DIN/ISO 3310	2 – 4 mm
Water content	(16± 2) %
Weight per volume	865± 100 g/l
PH value of pellets (T=20°C)	12 approx.
CO2 absorption capacity	Depending on the diving parameters and diving apparatus
NaOH content	Less than 4%

Dräger Divesorb Specification

Absorbent Canisters

The absorbent canister contains the absorbent material used for scrubbing CO_2 from expired air. The design of the canister influences the overall scrubbing behavior. The canister isolates the absorbent from surrounding environment, and defines the gas flow

Composition	Calcium Hydroxide > 75% Sodium Hydroxide 3 % Water
Color	White or Colored Solids
Density	2.0 g/cm^3
PH Value	12 - 14

Molecular Sofnolime Specification

inside the canister. The goal is to increase resident time, which is defined as the time the gas is exposed to the absorbent material. A short residence time normally causes an incomplete chemical reaction. Therefore, the CO_2 absorption capacity of the absorbent is

Photo by Sara Clarkin, LWDG

decreased. On the other hand, a long residence time requires a low flow rate through the canister. Generally, residence time of one second or more have been used in scrubbing design. Various tests have shown that residence time can vary from 1 to 0,1 seconds with respect to the different absorbents and still operate. With residence time less than 1 second, the CO_2 capacity of sodalime is greatly reduced (Wang, 1982).

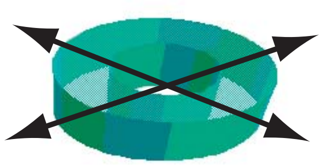
Axial Flow

The most common design is the axial Flow System. Gas flows through a block of absorbent in linear direction from one side to the other.

Axial Canister Design

Radial Flow

In some rebreathers, a radial design scrubber canister can be found. Gas enters through the center of a “Doughnut” cross-section and radiates either outwards or inwards through the absorbent.



Radial Flow Canister

This design is nevertheless bulkier than the axial, and is hardly found in rebreathers for recreational purposes.

Cross Flow

In a cross flow design gas flows through the absorbent block with a change in direction.

Various technical solutions are possible, mostly aiming to reduce any cooling by surrounding water and effective use of absorbent material. This design is not very common in diving, but finds its use in medical apparatus.

Cross Flow Canister

Analyzing a Rebreather

Since Henry Fleuss introduced a breathing apparatus as early as 1879, the basic design has been improved. But even today, all systems have in common a limited supply of breathing gas that is recycled, and the fact that CO_2 is chemically bound and replaced by oxygen. See Scheme of a Rebreather figure on following page.

CO_2 is an end product of metabolism. If increased levels are inspired, various symptoms can occur: 2.0% CO_2 content results in headache and increased

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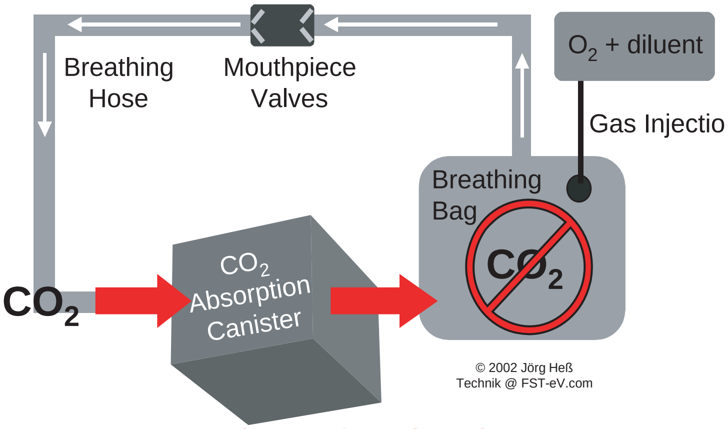


Scheme of a Rebreather

respiratory effort; 10% results in confusion and loss of consciousness within 2 hours. The US Navy considers CO_2 level as the key limiting factor for rebreather diving and submarine rescue (Curley, Office of Naval Research, Symposium 2001). A standard tolerable limit is defined at as 0.5% surface equivalent value (SEV), equal to 0.005 bar partial pressure of CO_2 (Curley 2001 and NEDU Technical Manual NO. 01-94).

The absorbent inside the canister or "scrubber" removes CO_2. A limited amount of absorbent can only last for a limited amount of time. It will eventually be used up, resulting in CO_2 passing through the canister. A level of 0.5% CO_2 SEV at the scrubber outlet defines the break through point and the end of scrubber life. This canister life is empirically tested under various conditions. In order to understand the overall absorption effect, the chemical reactions have to be investigated. Some rebreather behavior can be derived from this analysis. Nevertheless, the analysis is based on a dramatically simplified rebreather. A rebreather in real life is much more complex.

Chemical Reactions

Please allow the rather ignorant statement that classic chemistry to a great extent deals with the static end results. Most empirical functions to describe the chemical reactions are to provide a final ratio of components, or the total amount of heat produced once the reaction is completely finished, or a steady state in a continuous system has been reached. What makes the analysis of a rebreather so challenging is the fact that the rebreather diver operates in the gray area between starting a chemical reaction (the beginning of the dive), and reaching its final end (the absorbent is depleted, hopefully not before the end of the dive), while not allowing for a steady state by constantly changing the flow pattern (breathing). This analysis can therefore only provide a rough outline, extremely simplified. Nevertheless, even this simplification allows conclusions and provides some understanding of the scrubber performance.

There are many chemical reactions involved in the absorption of CO_2. Even after CO_2 has been successfully removed from the breathing gas, further cross-reactions between the products will occur. These are considered to have no effect on the absorption process itself. The search for the most important chemical reactions however is more difficult than some literature might suggest. Some chemical reactions that can be found in most of the literature actually turned out to be of secondary importance, because of the time required for the reaction itself, and the fraction to the overall absorption process.

The most important chemical reactions to scrub CO_2 are assumed as:

i. $CO_2 + H_2O \Leftrightarrow H_2CO_3$

ii.a $Ca(OH)_2 + H_2CO_3 \Leftrightarrow CaCO_3 + 2H_2O$

ii.b $NaOH + H_2CO_3 \Leftrightarrow NaHCO_3 + H_2O$

Most Important Chemical Reactions

Photo by Sara Clarkin, LWDG

These are equilibrium reactions, meaning two things:

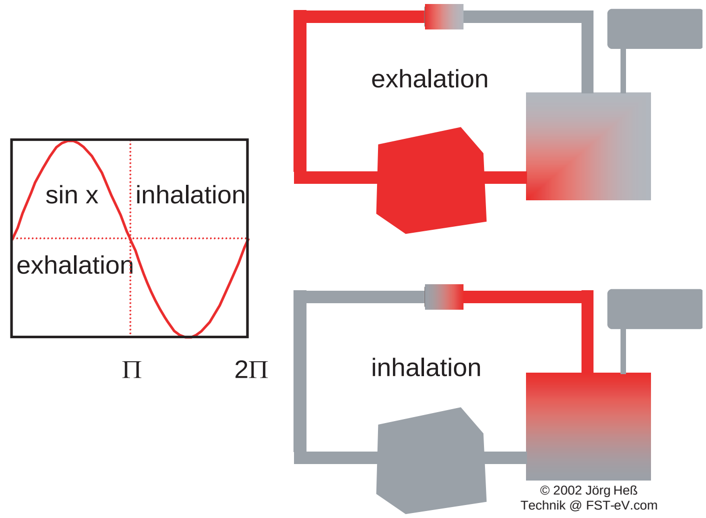
> *1. Both sides of the equation are always present. The reaction never proceeds from one side completely to the other. As a logical result, it is impossible for the absorbent to remove all of the CO_2. It will be reduced to a minimum – almost zero, but it will always be present!*
>
> *2. The chemical reactions function both ways. It is not a one way street, and it becomes possible for the absorbent to reverse-react, meaning to produce CO_2 while "recovering". It is strongly advised not to use this capability to "recharge" the absorbent, since no means of quality assurance is provided. The outcome is not guaranteed, it is rather more likely that an inappropriate attempt will result unsuccessful reversion. While diving, this furthermore poses a threat to the user, because it might increase the amount of inspired CO_2 under certain conditions. At this point, it remains a theoretical possibility that needs to be investigated.*

In the history of life support systems, other absorbent materials have been utilized. They mostly posed the danger of rapid reactions, resulting in excessive heat production, and an even more aggressive "caustic cocktail" if inspired. Sodium Hydroxide, NaOH, is one of these dangerous components. Sodium Hydroxide is still present in most common absorbents today, but it is restricted to less than 4% content. It is utilized to start the overall chemical reaction and to "warm up" the absorbent, especially in cold water. It reacts more readily than Calcium Hydroxide. After Sodium Hydroxide has reacted, it is most likely to remain in its resulting state, and is therefore used up.

In consequence, it can only be used once to activate the scrubber. It will not be available for a second dive. Under normal diving conditions, Sodium Hydroxide is not required, but it remains an important component for cold water diving.

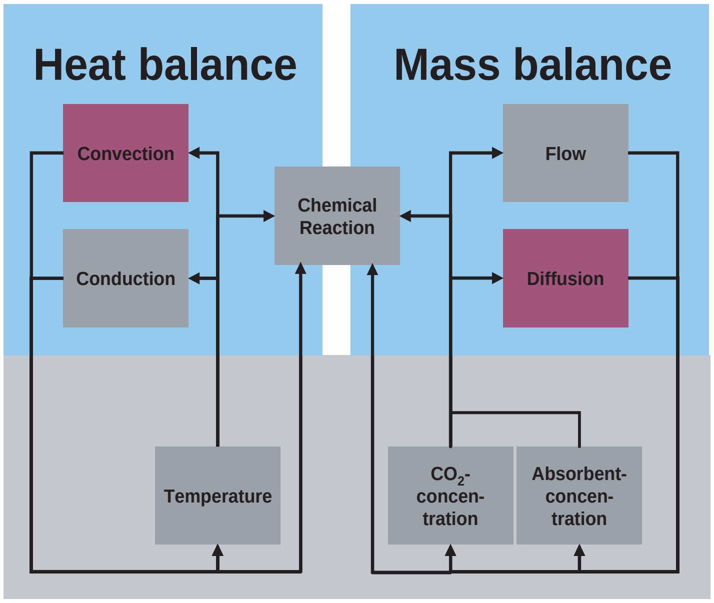
The Absorption Process

The rebreather breathing pattern consists of two reoccurring phases, exhalation and inhalation. Check valves in the rebreather's mouthpiece ensure the direction of flow. The breathing gas travels through different parts of the system, depending on the flow phase. In a very simplified view, exhaled gas flows through the canister into the inhalation bag during the exhalation phase. During the inhalation phase, previously exhaled gas stays in the canister. For simplification, the flow of CO_2 is described as a sine curve. Therefore, the flow through the canister follows a half-sine curve. In reality, an exhalation bag will buffer the flow, resulting in a more even flow throughout each cycle. The results presented here will therefore indicate a worst-case scenario.



Canister Flow Pattern

Notes:



Absorption Process Balance

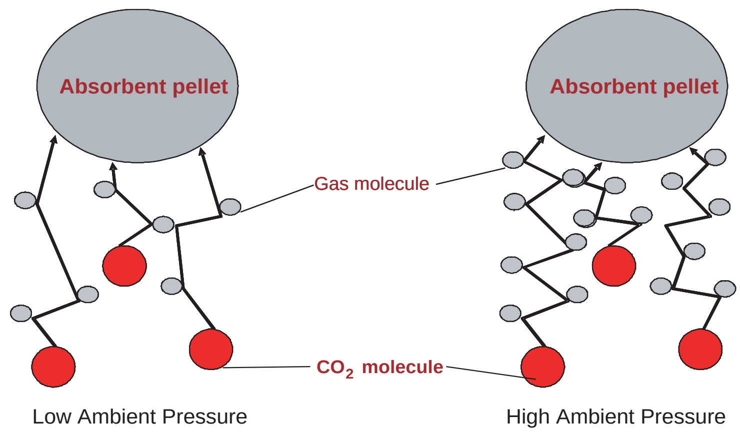
Heat balance describes the temperature depending on convection, conduction and chemical reaction. Increased temperature within the canister leads to increased chemical reactions, and increased heat loss through convection and conduction.

Mass balance describes the concentration of CO_2 as well as the concentration of absorbent depending on flow, diffusion and the chemical reactions. Increased concentration of CO_2 leads to increased chemical reactions. Flow and diffusion decrease concentration gradients.

Obviously, the absorption of CO_2 is dependant on more than one process and value. The different mechanisms in general counteract. Therefore, a prediction of canister behavior is not simple.

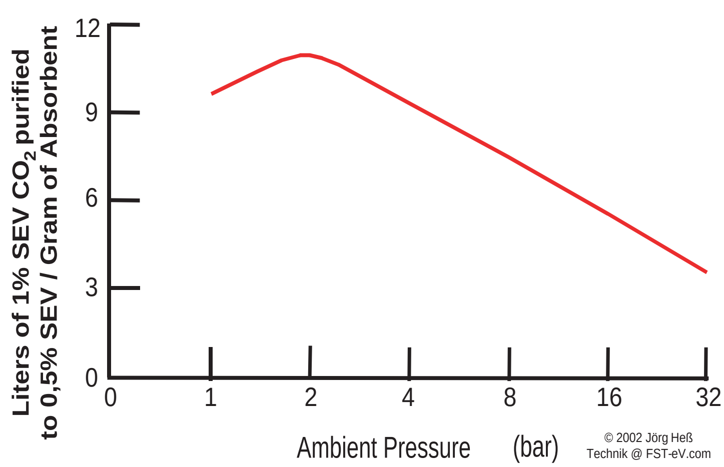
A change in the physical properties of the breathing gas mixture leads to a change in the process of **diffusion** and **convection**, and in consequence influences the absorption behavior. As a result, the absorption characteristics of the canister are dependent on depth, generally with decreased absorption capability with increased depth.

Diffusion means the journey of the CO_2 molecules towards the absorbent. The amount of CO_2, that is the number of molecules, or, as divers think of it, its partial pressure is not dependant on depth, since it is controlled only by the human metabolism. What is depth dependant is the amount of all the other gases in the breathing mixture, which results in a "diffusion barrier" with increased depth. Each CO_2 molecule has to pass by more other gas molecules as depth increases to reach the absorbent.



High Ambient Pressure Reduces Diffusion Speed Resulting in a 'Diffusion Barrier'

Convection is caused by the flow of diluent through the canister. Due to the heat produced by the chemical reaction inside the canister, diluent leaves the

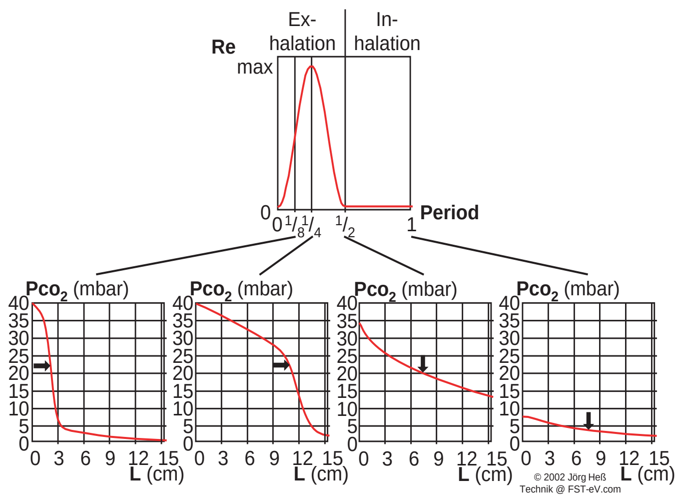


Depth Dependant Absorption

Notes:

canister hotter than it came in, effectively cooling the absorbent. The amount of diluent increases with depth, so does the cooling effect. Due to the sensitivity of the chemical reaction to temperature, the efficiency will decrease as a consequence. The theory of depth dependency is confirmed by measurements. A similar effect is derived with a change in breathing gas. Manufacturers' recommendations are not to be transferred to other gas mixtures. Taking the analysis to mathematical modeling of the axial absorber by means of finite element software leads to the visualization of the process results.

The figure below represents one breath out of a simulated 4 hour runtime.



Absorption Pattern of an Axial CO_2 Absorber

The concentration of CO_2 is set in relation to the flow status in the upper part of the picture. The breathing gas flows through the axial absorber from left to right. The abscissa (horizontal axis) represents the absorber's length; the ordinate (vertical axis) is the partial pressure of CO_2 as it can be found inside the canister.

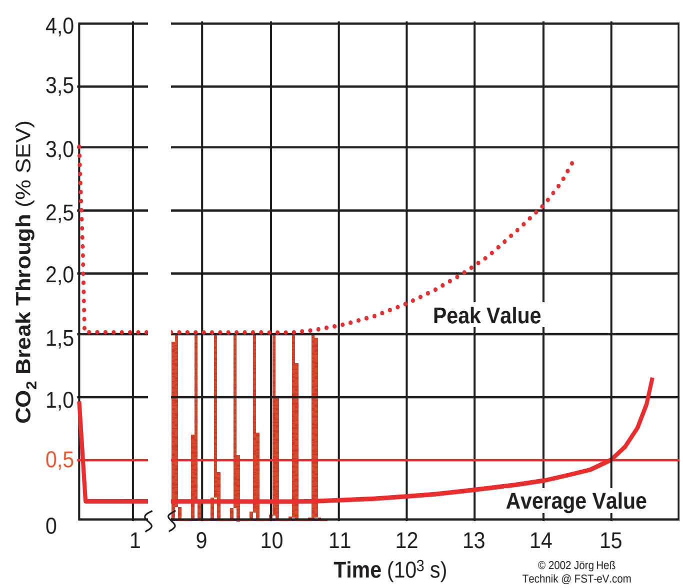
In the beginning of the exhalation phase, CO_2 travels into the absorber while being partially absorbed. The reaction zone then shifts further towards the absorber's end. Still, no CO_2 is present at the right side. The reaction zone travels wave-like through the absorber. After half the exhalation cycle, still no CO_2 reaches the end. At the end of the exhalation, CO_2 reaches the end at an increased level, resulting in a partial break through. Since the exhalation phase is almost terminated, the flow is close to zero. The amount of CO_2 that is braking through is small, and mixes with the gas in the breathing bag, thus averaging the level of CO_2 below the acceptable limit. During the following inhalation cycle, the remaining CO_2 reacts inside the scrubber. At the beginning of the next exhalation phase, nearly no CO_2 is left in the absorbent canister.

It is apparent that the whole canister reacts in the absorption process, not only a part of it. When reaching break through, the total amount of absorbent is not sufficient to ensure an acceptable limit of CO_2.

If the direct emission from the absorber canister is measured, an oscillating CO_2 concentration can be expected. Although the peak concentration of CO_2 is fairly high, the average CO_2 level is initially low. When reaching the end of the canister's life, the average level of CO_2 will rise exponentially. A characteristic break through pattern is displayed in the next graphic. This behavior is confirmed empirically (compare Dowgul, 1982 and Aqua-Lung, U1010.14).

In this graphic the simulated absorber's duration is 4 hours or 14,400 seconds. It can be expected that 10 minutes later, the acceptable limit will be reached.

After 4 hours and 15 minutes, serious results occur. Under real conditions, this small margin can shift towards a shorter time of usage due to improper canister filling (channeling), differences in the efficiency of the absorbent (it varies from batch to batch), temperature, increased CO_2 production by the diver, etc. The point of break through is then reached much sooner.



Characteristic Break Through Pattern

Putting it Together

The analysis allows drawing conclusions and explaining the effects for various diving conditions. It is, however, only a hypothetical approach, and the final determination has to be made by near-life experiments under controlled conditions.

> **"The purpose of a CO_2 absorption canister is that it removes CO_2. It is a machine that performs... until it runs out of power."**

Which Absorbent is Best

The choice of absorbent is certainly not easy, with different manufacturers offering so many products. While they all rely on the same chemical concept, the absorbents differ in physical shape, and chemical composition. Sometimes differences are not obvious to the naked eye. The performance, however, may differ greatly. It is not possible to transfer experience and measurement results from one canister to another, and while one absorbent performs dutifully in an axial canister, one can be surprised to find insufficient absorption in a radial canister with the same absorbent (Clarke, 2003). As long as no valid measurement data is available, the user should stick with the manufacturer's recommendation.

Packing the Canister

According to the simulation results, one of the major influence factors to the overall canister performance is the "interstitial volume," meaning the space between the absorbent pellets. It is partially determined by the absorbent's physical shape. The user's influence is the proper packing of the canister. Channeling will void any efforts to provide proper reduction of CO_2. It becomes a result of improper filling absorbent granules into the canister, with too much space in between. Shaking the rebreather during transportation will settle the absorbent, and the open spaces will "accumulate." These channels then allow exhaled gas to follow the route of least resistance and bypass the absorbent.

Properly filling the canister requires some time. Tapping the canister between filling it with layers of absorbent allows the pellets to settle into the densest form. Overfilling the canister however will result in crushing the pellets when forcing the canister lid closed. Absorbent dust from crushed pellets will clog the interstitial volumes, which will reduce efficiency as well.

Different Gas Mixtures

Different gas mixtures will behave differently inside the absorbent canister. Oxygen and nitrogen are very similar in their thermal values, so any nitrox mixture will behave similar.

Introducing helium as a breathing gas becomes a different matter. Helium has a higher heat capacity per mass, but is less dense. The amount of heat per volume introduced by helium into the absorbent canister is less than with nitrox. Although the temperature of the helium may be the same, the resulting canister temperature will differ. Rebreather systems for deep diving usually have a big canister, which takes care of the depth, dependant reduced efficiency, breathing gas dependency, and the usually extended bottom time that is required.

Pre-Breathing

When the canister is first breathed, a high level of CO_2 will pass through the absorbent. As the absorbent is warmed and as the moisture content of the absorbent increases, more CO_2 will be absorbed and little CO_2 will pass through. The canister is "warmed up", and the chemical reactions are started. The initial high level of CO_2 break through is reduced to an acceptable limit within the first few minutes of use. This explains why it is important to comply with the manufacturers' recommendation to pre-breathe the canister on land for 3 to 5 minutes before diving. Pre-breathing has to be done under controlled conditions at the surface. Any exertion (elevated production of CO_2 by the diver) during this time frame can easily lead to over-breathing the canister.

Over-Breathing

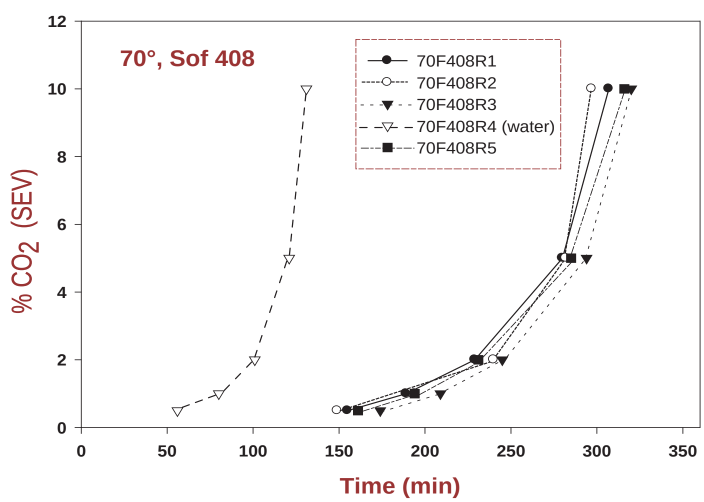
In the case of an increased flow rate, a greater fraction of CO_2 will pass through the absorber, resulting in a higher level of CO_2 in the inhaled gas. If the rebreather is not designed for high stress, it should never be used under high workload. As shown, it is easy to over-breathe the canister. The system can "recover" by reducing the workload. This does not mean that the absorber "recharges", it simply enables the canister to pick up its designated task again by increasing the time the gas spends inside the absorber.

End of Canister Life

It becomes obvious that a absorbent canister can not be utilized beyond its life span. Measurements can confirm the rapid increase of CO_2 once the canister is spent. This effect becomes even more rapid under workload when CO_2 production is increased. Once the canister has performed dutifully, it cannot be "recharged." Flushing the system does not re-activate the scrubber. It simply removes the small amount of CO_2 in the loop. Within minutes, a critical level of CO_2 will be exceeded again.

Water Temperature

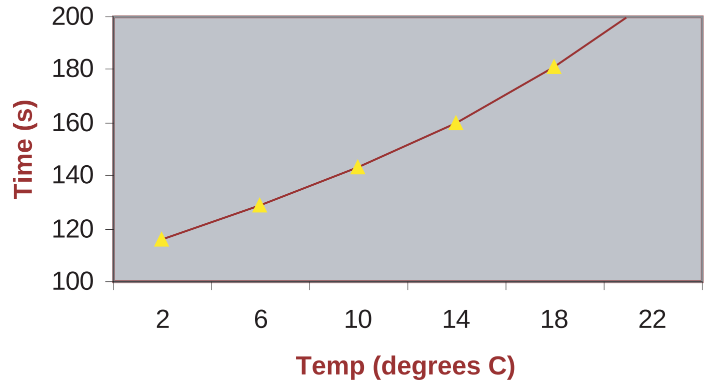
The speed of the fundamental reactions is



Measurements Confirm the Rapid End of Performance (Clarke 2003

temperature dependent. Increased temperature leads to increased speed of reaction. The absorbent then reacts more readily, which will usually result in a higher efficiency of the scrubber in warm water.

The old US Navy Diving Manual provides Navy divers with a chart to estimate the LAR V canister duration depending on the water temperature.



Canister Duration vs. Temperature

Different manufacturers have different experiences with different units. Ambient Pressure Diving could only measure an insignificant increase of canister duration in warm water (Parker, 2003).

Since most canisters are well insulated, the water temperature will not directly affect the chemical reactions. The inflowing gas temperature however, indirectly influences the reactions. This influence is two-fold. Cool gas will reduce the reaction speed, but provide more liquid water caused by condensation. As seen from the chemical reactions, water is required to perform the absorption. Warm gas increases reaction speed, but will not provide as much condensation.

Depth Dependency

Although the influence of depth on the scrubber performance is minor in relation to other factors, it can contribute to over-breathing or exceeded end-of-canister-life. Exceeding the rated operation depth will contribute to the risk of over-breathing and end-of-canister-life.

Conclusion

Exceeding tested conditions works in the vast majority of dives – so does driving without a safety belt.

Chapter 5 - CO_2 Detection

by Joerg Hess, M.S.

The desire to measure CO_2 in rebreathers is as old as its technical solution. Human physiology is very susceptible to CO_2, yet it does not provide a reliable warning. The demand for technical CO_2 sensors is almost desperate. Unfortunately, since CO_2 content cannot be measured, its role and danger in rebreather diving is widely underestimated and ignored.

The concept of the research project RCAP was to analyze absorbent canisters for possible measurements and estimate CO_2 contents in the breathing gas. During the first months of the one-year project it became obvious that this is not likely.

What's the Problem?

One way of measuring gas contents are optical gas sensors. They are based on the gases' unique infrared (IR) absorption signatures of most gases. This identifies and quantifies chemicals, in liquid and gas phase mixtures, with little interference from other gases. As basic IR gas sensors operate an emitter produces infrared illumination. The target gas enters the sampling region and some of the infrared illumination is absorbed. The exact amount depends on the concentration of the gas. The detector measures this decreased transmission. This method of measuring CO_2 levels is non-dispersive infrared (NDIR). Nevertheless, it depends on the substance being tested to be in gas phase. If water droplets hit either side of the optics, measurements are inaccurate.

Basic Optical Gas Sensor Principle

The problem with measuring CO_2 levels in rebreathers is the relative 100% humidity. Water droplets in the optical system of the sensor lead to false alarm. At the time this chapter was produced an Optical Sensor utilizing a hydrophobic membrane has been successfully designed and tested (Israeli Navy and others) but is not widely available.

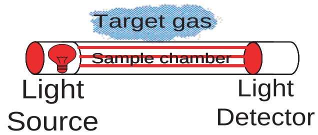
Chemical sensors exist for O_2. Even these are subject to interference from variables like temperature and moisture. The goal is to eliminate these side effects or shift them outside the working parameters of the sensor. A high accuracy is achieved when the sensor comes pre-packed, with little user handling.

Chemically sensing CO_2 in a small portable system is not possible; many approaches have been tried and none have proved possible in rebreathers.

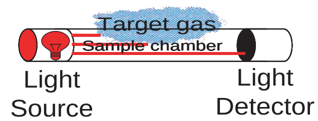
Working Around the Problem

A possible solution to this dilemma is to use the CO_2 scrubber inside the counter-breathing device as sensing platform. Several ideas keep reoccurring in the history of rebreathers, but with research failing to produce sensors, little or no documentation is available.

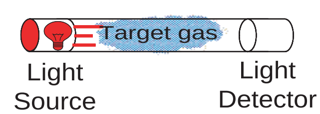
Since directly measuring CO_2 is not possible yet, the next step is measuring the status of the scrubber. This indicates its absorption capacity. The idea is that a "bad" scrubber will result in high levels of CO_2. Unfortunately, this does not include that a "good" scrubber will have no CO_2 in the emitted breathing gas. There are a number of reasons for undetected break-through. Increased breathing will lead to increased levels of CO_2, even in a working scrubber, and channeling cannot be sensed. These are just two examples of failure modes that remain undetected by scrubber measurement.



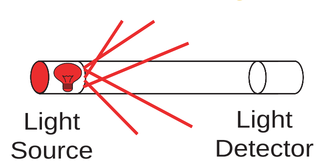
No Light Absorption
No Warning



Some Light Absorption
No Warning



Light Absorption
Warning!!!



Water on Lens Refracts Light
False Warning

Scrubber Testing Misconceptions

Without conceptualizing the exact method of absorbent status measurement, understand this is a concept - not measuring CO_2 itself - but trying to determine an indicator for the gas. So the path of research moves away from the original goal and introduces error and uncertainty. Further deviance will increase overall errors, resulting in inaccurate statements.

Two Possible Detours

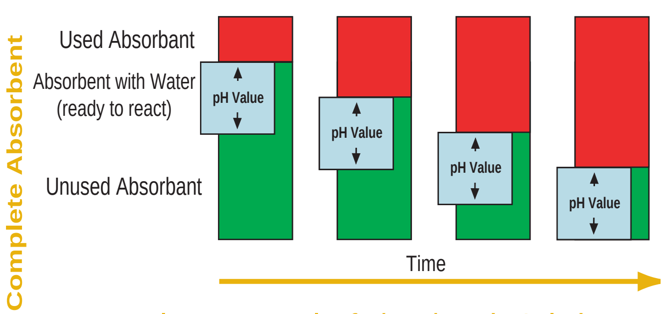
Measuring scrubber status is impossible in a portable system. The requirements include measuring absorbent availability and distribution, water content, flow rate, ambient water temp and pressure… to name a few. Ironically, the canister's performance is also influenced by CO_2 partial pressure variations. CO_2 measurement is required to determine proper canister status, which was impossible to measure in the first place.

Detour 1 - pH Value:

If these variables could be anticipated, the actual non-destructive measurement of absorbent availability poses a sensory problem. The amount or concentration of absorbent must be field-tested under controlled conditions to measure its reaction with chemical substances. Measure the ph value; as long as it maintains a high pH it's capable of scrubbing CO_2. The conceptual problem is that only a part of the absorbent is in reactive solution while the rest remains "sleeping" in solid form. When the reactive parts are used up, they will drop out, leaving water for the remaining absorbent to dissolve in. The result is a constant pH value until all absorbent is used. This will be long after the overall canister failed to perform accurately. So, the pH value is not an option.

Detour 2 – Temperature:

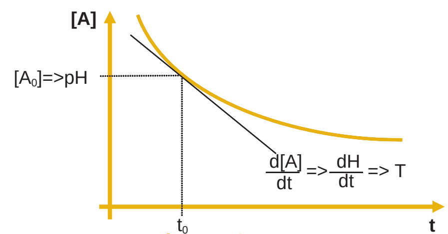
Taking it one step further away from the original goal is measuring the degradation of the scrubber, hence knowing the status by its decomposition. This way of indirect-indirect measurement by concept also introduces more uncertainty and failure points, again independent of accuracy and means of the actual measurement.



pH Value as a Result of Absorbent in Solution

A 20-year-old reinvented concept is the idea of using temperature probes in scrubber canister. As every rebreather diver knows, the canister heats up during the dive so temperature provides some indication. The basic misconception associated with this idea is an assumed direct correlation between the temperature and the chemical reaction.

Again, if measuring temperature indicated chemical processes, it would not indicate an increased CO_2



pH Value and Temperature
as Result of Absorbent Degradation

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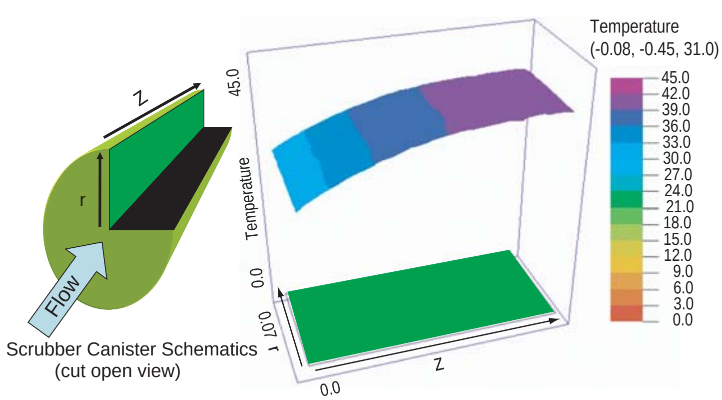
concentration downstream of the scrubber.

The chemical process requires optimal circumstances. If any of these fail, it will not reduce CO_2 concentration and the temperature will drop.

Absorbent concentration degradation (d[A]) results in enthalpy change (dH) over time. This produces heat.

Measuring temperature indicates degradation speed. Temperature is a process value, not a status value. The scrubber status is still unknown. It might

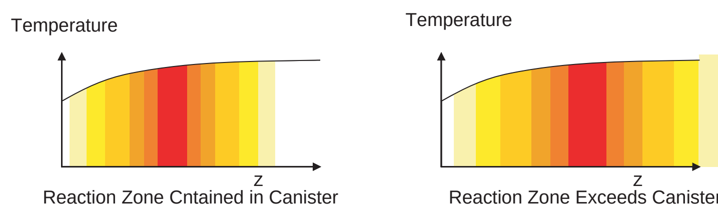


Typical Temperature Profile Inside Scrubber

be possible to integrate the degradation over time. This requires any calculation to start with a "fresh" scrubber of known condition. Any deviance from the real scrubber to the computed model leads to improper results.

Due to the high heat capacity of the absorbent, minor temperature changes will occur in the immediate area surrounding an absorbent pellet. Furthermore, temperature is not a direct result of enthalpy change. It indicates heat loss through canister walls. Different gas temperatures result from different breathing rates. Overall, temperature does not directly correlate with the chemical process.

The reaction zone in an axial scrubber produces heat in the upstream portion. That heat is pushed through and eventually reaches the end. Due to canister insulation, an established temperature curve remains stable. This masks the end of the reaction zone, which is crucial. The temperature might only indicate the start of the reaction zone, but no indication of CO_2 break through is visible.



Stable Temperature Profile Masks Reaction Zone

New Temperature Sensing Technology

Tracking temperature as a means of monitoring the CO_2 levels in a canister may be a debatable process, but nonetheless it is one approach to the problem. The US Navy, and OMG in Italy with the Nemesis CCR, has pursued this approach. The Megalodon, although making no claims to CO_2 prediction, does use a loop and ambient temperature tracking that may provide insight on scrubber breakthrough.

Temperature as a means to predict the CO_2 level the canister is also a major feature in the Vision electronics developed for the Evolution CCR by Ambient Pressure Diving (AP). These same electronics are available as an option in the Inspiration. Martin Parker describes the Vision electronics approach:

"During our unmanned CO_2 scrubber trials on the Inspiration and Evolution, at the UK Royal Navy test facility, it became clear that giving the diver a warning once the canister is at breakthrough is too late. We needed a system that would predict when the scrubber was coming to the end of its life before actual breakthrough.

The new scrubber gauge for the Evolution monitors the temperature through the sofnolime bed by using temperature sensors molded into the center stem of the canister.

It's a system, which works well to give an advanced prediction of how much of the scrubber material has been used, for the purpose of determining the end of the scrubber material. This system when compared to a CO_2 sensor has the advantages of being cheaper, more robust, more reliable, uses less power, is unaffected by moisture and gives warnings in advance of CO_2 breakthrough. It compensates for depth too, and works at different gas temperatures, as well as automatically compensating for lower or higher work rates.

By monitoring exactly what is happening to the scrubber material, the system automatically reflects the reduced performance of the scrubber when deep and then gives you longer duration as you ascend.

We have a linear display showing the active and inactive areas of the scrubber and then with software we change the display towards the end of the scrubber life so the display works like a fuel gauge on a car (i.e. when the display is empty, you have no more scrubber time left.) Just before it becomes empty, you get a CO_2 scrubber warning on the Head Up Display and the wrist-mounted display, including a buzzer alarm, which you can then suppress. When the indicator bar is empty an insuppressible CO_2 scrubber warning is sounded. If you ascend and reduce your work rate (switch to OC) and if the scrubber bed recovers slightly during ascent, the display may revert back to showing one black segment on the right side of the display. The continuous CO_2 scrubber warning is then suppressible for 5 minutes at a time or until the scrubber is further depleted.

It does not detect CO_2 if the CO_2 is bypassing the canister, because of for example: damaged/missing O-ring(s), damaged/missing non-return valves in the mouthpiece, or lack of sofnolime - our system doesn't warn the diver. We are only able to show what is happening to the scrubber material itself."

The new technology presented by AP is a magnificent tool to better understand the working progress of the CO_2 scrubber. It is based on a prediction model. It allows cautioning the user should the scrubber not cope with the demand.

Conclusion

The theory behind these concepts suggests a high risk of inaccuracy. That means the performed measurements will lead to the correct results sometimes. In rare occasions, the results will not be accurate at all. "Rare" is a relative term. A 99.9 % accuracy means 1 in 10 divers performing 100 rebreather dives annually will not have a chance to celebrate the next year. The problem is making the concept user-friendly. Even if a hypothetical sensing system is introduced for extra safety, users will rely on it as a positive indicator and push the limits as long as no warning is displayed. The result will be incidents due to undetected canister failures. Similar occurrences are in the history of rebreather diving. Today, the argument still is "I didn't get a problem on my 1-2-3 dives, so it must be working".

The user has to make up for the system's deficiency and fortunately is trained to do so. Every diver may choose to avoid the risk of hypercapnia or to rely on equipment with his or her life.

Notes:

Chapter 6 - Equipment

by Tom Mount, D.Sc., Ph.D.

Developing a smooth, streamlined underwater swimming style takes practice and an understanding of proper technique. Equally important, however, is the way in which your dive equipment/gear is configured and carried. Improper gear configurations cause excess drag, are more likely to cause entanglement problems, and can make it difficult or even impossible for the diver to access needed backup equipment. Proper configuration, on the other hand, allows the diver to minimize underwater drag, protects the equipment and allows for immediate access to all primary life support gear and important backup items.

Beyond these universal factors, there are endless variations on the specifics of proper gear configuration, especially with rebreathers due to their different design configurations. Differences in the diving environments and in diving styles place widely varying demands on equipment and a rig that might be perfect for Normoxic Trimix diving could be totally wrong for confined sump dives.

Safety is the first consideration that must be addressed when planning an equipment configuration. The diving mission often dictates the gear to be carried - and it may have some influence of how that gear is worn. As the diver selects gear to match the dive's requirements, he should analyze each specific piece of hardware, and should select only items that will contribute to the overall safety and performance of the dive. Without a safe system, all other effort is wasted. Before designing a personal system, listen to the experiences of other divers and review accident case studies. By identifying potential problem areas, you can then create a rig that is not only personalized to your needs and habits, but is also created with maximum safety in mind.

Photo by Curt Bowen

Universal Considerations of the Rebreather Diving Kit

Comfort and fit are key to the enjoyment of any dive, but become increasingly important to diver safety within the context of the longer, more demanding scenarios of rebreather diving. An uncomfortable diver is more susceptible to stress, will tire sooner and may experience perceptual narrowing caused by the discomfort of the equipment. By contrast, a comfortable diver is more likely to remain alert, relaxed and aware of his surroundings, all of which contribute to dive performance and emergency preparedness.

In addition to providing a comfortable fit, the kit must be stable, even when all the accessories are added. Also keep in mind that your chosen kit should not only be comfortable in the water, but also on land. This is particularly important in cases where you are required to wait before entering the water, or to walk some distance to the dive site. If you are currently using a system that causes discomfort or pain, analyze the points causing the discomfort and make an immediate change.

Redundancy is unquestionably technical diving's single greatest safety margin. The philosophy of redundancy dictates that a bailout rebreather or OC bailout should back-up any element of the diving rig that is essential to life support. Problems arise when divers carry the philosophy of redundancy too far, however. There is seldom any need for multiple backup systems, and excessive redundancy not only creates configuration problems, but also may actually decrease the overall safety of the diver by adding a layer of confusion as they search through every possible option.

Items that serve as a back up include bailout systems. These may be either an OC bailout or a bailout rebreather. Lights in cave and wreck diving also require back-up. In some cases it may be desirable to back up the buoyancy control system. This may incorporate a dry suit with one BCD or a wetsuit with two BCDs. The counterlungs may also provide bailout buoyancy control especially at the surface. Another item worthy of back-up is the cutting tool. This may be a small knife, surgical scissors or other instrument. For wreck diving, the cutting tools must be able to cut wiring and fishing line and should be placed within easy reach.

Self-sufficiency combined with the ability to perform self-rescue is the primary requirement of any CCR diving kit. The design must allow the diver quick access to any self-rescue items and provide a realistic degree of self-sufficiency. There is no advantage to carrying surplus safety items - there may be disadvantages. Too much of a "good thing" may result in decreased performance instead of enhanced

Notes:

20 Equipment Configuration Essentials (in order of importance)

1. Safe & Dependable
2. Comfortable
3. Adequate redundancy (not excessive)
4. Self-sufficient & self-rescue capability
5. Simple & user-friendly (KISS principle)
6. Valves & accessories are easily reached
7. Buddy rescue & assist capability
8. Fits the diver's needs & dive objectives
9. Confidence in the configuration
10. Low drag profile.
11. Balanced & good swim attitude
12. Equipment identifiable by touch
13. Standard gear placement
14. Versatile
15. Streamlined & Clean
16. Modifications made at diver's discretion
17. ID bailout cylinders by sight & touch
18. Label cylinders for intended use
19. Team equipment compatibility
20. Continue to improve configuration

Photo by Tom Mount

stages and switching bailout stages with the buddy enables all divers to always have adequate bailout and to be able to swim at a normal swim pace with out being hampered by attachment to the buddy diver.

The dive team should have adequate bailout gas to get 1½ divers up to the surface or to anther source of gas. To fulfill this requirement, in some occasions cylinders may be staged at various locations such as in cave and wreck diving. Another method that allows for this capability is the use of a longer second stage hose attached to either the rebreather directly such as on a Cis-Lunar MK 5 with its gas switch block capability or to the first stage regulator on the stage cylinder. This hose should be 5 feet or longer.

capabilities. Treat each dive as if you were diving solo. Do not be dependent upon others for your safety. A self-sufficient diver is a survivor. The majority of times when an OC diver is having a problem it is apparent, and a buddy can easily and quickly come to their aid. However, on a CCR it is unlikely a buddy could recognize many physiological problems or equipment related issues. For this reason a CCR diver must be extremely self-sufficient.

Keep the kit configuration simple and it will serve you better. Elaborate and complex gear placement leads to confusion in times of stress. If the configuration is simple and easy to use, then it is ideal. If the complexity causes one to stop and think in order to determine where a needed piece of hardware is located, it will not suffice in a fast-moving, stressful situation. Tank valves must be reachable and accessory equipment must be rigged in a fashion and a position to be readily available.

The ability to perform buddy rescue or a buddy assist is a mandatory component of any diving rig. The preferred method of managing a gas management emergency is to have the distressed diver bailout to their OC stage or bailout rebreather. If bail out is to OC the diver will use ½ of their OC bailout and then switch cylinders with the buddy diver. The use of bailout

The hose must also be easy to deploy and hand off to a distressed diver. Before a dive, buddies should familiarize themselves with the location of each other's safety and backup equipment, and should also check each item to make sure it is functional and configured to facilitate self-sufficiancy as much as is possible. Dive teams that work together on a regular basis might wish to go one step further and work towards a common, mutually agreeable means of configuration and positioning of the life support systems involved in buddy rescue.

Out-of-the-box diving equipment seldom meets all the specialized needs of technical diving. As a result, most technical divers have learned to customize their equipment to fit the specific needs of the mission. Before you can effectively customize your equipment for the best possible fit and function, you need to build a basic understanding of each piece of equipment that will make up the kit, and also gain some understanding of how these parts come together as a whole. Therefore, you should be willing to set aside a reasonable amount of time to analyze the components of the system and then determine how you want them to blend into a usable whole.

Regardless of your customizing efforts, the end result should inspire confidence in your kit, and should allow you to operate with minimal effort and maximum comfort. A streamlined diver creates less drag in the water. By streamlining, you lower the work of swimming and, in turn, increase your comfort level. A streamlined configuration also assists in avoiding entanglement and the possibility of becoming stuck in restricted areas.

Once you have selected and assembled your kit, you must look for ways to streamline and clean up the loose ends. Begin with careful scrutiny of each piece of equipment, looking for ways to streamline it to the point of least possible drag and bulk.

A streamlined kit will have few or no hoses protruding. Hoses must be stored neatly and gauges must be secured snug to the body. Accessory items should also be attached to minimize drag and the chance of entanglement. In general, you will want to avoid all dangling objects and items attached to the harness by a single clip or strap that allows for excessive movement.

One additional factor to consider when constructing an equipment configuration is the need to create a balanced swim posture. A kit that does not allow the diver to maintain a comfortable horizontal swim position is not suitable for the majority of technical diving applications. Any kit that is inherently unstable or which requires excessive effort to maintain a swimming position should be reconfigured or modified to alleviate the problem.

An effective CCR diving rig should be balanced, comfortable and streamlined. It should provide for a standardized method of gear placement, but must also allow room for improvement or innovation. Each item of equipment should be easily identified by touch and visual identification. In addition, the system should be versatile, allowing you to transition smoothly from one diving environment to another with ease and comfort.

All cylinders used on a dive must be properly labeled. A number of fatalities, including those involving highly trained technical divers, can be directly attributed to a failure to identify and label breathing gasses. When using any gas other than air, you must analyze, identify and label the mixture.

The mouthpiece of the bailout cylinder with the highest EANx or Oxygen content should be covered or have rubber tubing or similar protection wrapped around it. This prevents accidental switches to the wrong gas at any depth. The diver cannot breathe from it until the cover or tubing is removed from the mouthpiece. Do not allow something as simple as a cylinder mix-up to cause an accident. Rig your kit in a consistant manner and always label your tanks thoroughly.

Underwater Lighting

Lights should be evaluated with regards to depth ratings, illumination power, burn time, ease of storage and performance. When diving in overhead environments beyond the point of surface light, the diver must carry a primary light and two smaller secondary lights. If diving within a zone of surface light, a primary and one backup will suffice.

The physical positioning of the primary light varies widely among divers, but the three most popular methods are either waist mounted, backplate mounted, or butt mounted. Regardless of which method you choose, you should be aware of the advantages and disadvantages of both systems. More information on these methods is available in the IANTD *Technical Diver Encyclopedia*. Additionally, you should be aware of how to use any alternate method. Some diving environments are served better by one method, more so than another. Safety lights should be carried in a

Photo by Pete Nawrocky

Notes:

manner that minimizes drag while allowing for quick, easy access.

Buoyancy Compensation

The majority of rebreather and technical divers prefer the back-mounted flotation systems typically known as wings. Wing systems conform to the profile of the CCR. Ideally wings used on a CCR will have a trim neck profile and flare out towards the bottom portion of the wings so that additional lift is in the area of the cylinder valves. This type wing is a great aid to improving the trim on many CCR's.

When selecting a buoyancy compensation system, make sure it has adequate lift capacity to support you and all the equipment you plan to carry, not only on the surface, but at depth, where compression will reduce the inherent buoyancy of a wetsuit or neoprene dry suit. On the other hand do not use a system that has excessive lift and size, as it will add to the drag profile of the system.

Diver error or faulty maintenance causes the majority of buoyancy compensator failures. Common causes of failure include pulling too hard on dump valves, snagging or abrading the air bladder on an environmental feature and allowing sand or debris to clog a dump valve seal. But even if you take exemplary care of your BC system, there is always some chance that an air bladder failure will cause you to lose buoyancy. Lift bags, while not strictly a buoyancy compensation device, are also a needed part of open water technical diving rigs. Bags should have at least 25 pounds of lift and the uninflated bag should be stored in a manner that minimizes drag and the chance of entanglement. The lift bag may also be used for buoyancy compensation in an emergency condition. In this case it can be used as a pillow placed under the diver or it may be deployed to the surface and the diver can reel themselves up on it.

Cutting Tools

Technical divers carry cutting tools not for the purpose of dismantling artifacts or the environment, but to extract themselves from entanglements. The cutting tool should be appropriate for the diving environment. For example, a lightweight parachute cutter would suffice in a cave, where the only entanglement potential comes from nylon guidelines. Heavy wire cutters are more appropriate for diving on wrecks draped in dangling cables, wires and discarded fishing nets. Surgical scissors typically work well in any environment and will cut either wire or line.

Reels

You must carry a safety reel on all technical dives, as it is a primary tool of self-rescue. If you become lost, disoriented or separated from a guideline in an overhead environment, the safety reel can be attached to a reference point, allowing you to perform search sweeps without straying further from the point of the initial problem. In open water, the safety reel can be used to deploy a lift bag.

In caves, and on wrecks of major magnitude, you or some member of the dive team should also carry a larger, primary reel, which will be used to form a continuous guideline to open water, either by deploying line throughout the dive, or tying into an existing guideline. Cave dives that call for jumps from one existing guideline to another will require

"Always remain an individual & use freedom of choice... Remember, the final word on configuration is yours."

additional small reels known as gap reels. Your dive team should carry one gap reel for every expected line jump, but there is no advantage to carrying more reels than the dive plan calls for.

Pressure Gauges

The large gauge consoles common in open water recreational diving do not find favor with technical divers. Instead, pressure gauges are typically fitted with a minimal cover boot, and are attached to a harness D-ring or stowed close to the diver's body to prevent entanglement.

Exposure Suits

Because technical dives typically last much longer than recreational dives, heat loss becomes a concern much sooner. A reduced body temperature is a predisposing factor to DCS, so exposure protection is not only a matter of comfort, but also a safety concern.

In warm or temperate waters, many divers opt for the relative simplicity of a wetsuit, and may include a hood or hooded vest for longer duration dives. As in-water times increase and water temperatures decrease, most veteran technical divers will opt for a drysuit. Before diving a drysuit, you should seek additional specialized training in its use and maintenance.

Accessories

Items such as masks and fins should be selected on the basis of personal comfort, fit and durability. Because the additional gear you carry on a technical dive increases your underwater mass and profile, your fins should be large and stiff enough to move you without causing excessive leg fatigue.

Stage Tanks

In CCR diving, additional gas supplies are often needed to either extend the bailout range for exploration or to supply decompression mixes. To accommodate these gas needs, divers may carry permanent, semi-permanent or removable stage tanks.

Removable stage tanks are the most common option used by CCR divers. But before discussing the particulars of removable stage bottles, we should review the other two options.

Some divers use pony bottles, attached to the back of the rig for bailout. The Cis-Lunar MK 5P was designed specifically for this application.

If a pony bottle is to be used as a safety tank, it is recommended that the pony contain a minimum of the sum of the amount of team gas to get one and one half divers to the surface or additional staged gas supplies. For instance if it is a two man team and based on the highest team members RRV, it would take 80 ft^3 of gas (2400 L) to get a diver to the surface, then the team would have to carry 80 + 40 ft^3 = 120 ft^3 of gas 2400 + 1200 = 3600 L). In a two-person team each diver would be required to carry 60 ft^3 (1800 L) of gas volume. In other words, in a three-person team each member would have to carry a minimum 120 divided by 3 = 40 ft^3 (3600/3 = 1200 L) of gas.

Photo by Steve Millard

In exploration diving, the concept of staging a portion of the gas is a popular practice. Cave exploration entered a new dimension when the concept of stage diving evolved. The practice was initiated by Sheck Exley and named by this author. For CCR divers this allows safer bailout scenarios with out having to be overly inhibited by carrying too much bailout gas. Then, by dropping the stage tank off at a predetermined point - or a point based on bailout gas needs by the stage cylinder - the divers can reduce drag and increase their overall swimming efficiency.

During wreck penetration dives, the ability to drop stage tanks in open water reduces the risk of entanglement. In addition, the diver may then be able to fit into more confined areas of the wreck. In IANTD technical diving courses, standardized training requirements call for the use of stage tanks.

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In addition, the second stage should be attached to the stage tank by either a hook or secured by surgical tubing. This attachment must be easy to reach, to attach, and to remove while swimming. The physical placement of the stage bottle on the diver can have dramatic effects on his swim posture and drag profile. The majority of divers attach stage bottles on a D-ring high up on the shoulder and a waist D-ring on the harness. The snaps and support attachments are close to the bottle to reduce drag, and are positioned to keep the tank close to the diver's body. Each diver must arrive at a personal balance between a snug, streamlined and flexible configuration that allows for easy access, attachment and removal.

Before using stage tanks, divers should seek formal training in their use. Most respected technical diving courses devote considerable time to stage tank management. IANTD's Tek CCR course Standards require you to use and properly manage all aspects of stage tank diving technique. You will practice removal, staging and retrieval of the tanks until the operation can be performed flawlessly without a change of swim pace. Moreover, the diver must be able to place the proper tank at the correct location simply by feel in low to no visiblity situations. This is accomplished by practicing with closed eyes and by ensuring each stage bottle can be identified by the difference in its support attachments or by the difference in regulator design.

In some ways, staging tanks is similar to flying an airplane; one must think ahead of their present position, and anticipate upcoming actions. As a diver approaches the point at which a stage is to be dropped, the tank should already be removed from the harness and held ready to deploy.

Stage bottles should always be rigged and worn in a manner that allows them to be retrieved with ease. As the diver picks up a stage tank, he should be prepared to make buoyancy changes and to attach the bottle with a minimum of delay. The ability to retrieve stages efficiently prevents silting on wrecks and in caves, and also reduces additional bottom time. In too many cases, divers who lacked the necessary stage handling skills have either totally silted out the environment or added significant decompression time to their dive due solely to slow stage retrieval.

Conclusion

In summary the selection of the proper equipment for a given dive, combined with a configuration that fulfills the 20 requirements outlined in this chapter will provide more enjoyable and safer dives. The CCR diver must always be alert and totally familiar with their unit and able to easily and comfortably access all components of the system.

Photo by Pete Nawrocky

Chapter 7 - CCR Diving Accidents

by Tom Mount, D.Sc., Ph.D.

Accident-free diving doesn't just happen. It is the product of a comprehensive effort that includes awareness, training, ongoing practice and planning. Many factors contribute to diving accidents, and an equal number of behaviors and practices reduce the likelihood of these accidents. In this chapter we will look at some common causes of accidents, along with the most practical preventative measures and solutions to avoid accidents.

Photo Courtesy of Steam Machines

Accident analysis is based on a continual review of the causes and potential prevention of accidents. The facts and opinions shared here are based on documentation and the collective experiences and opinions of numerous CCR diving experts.

As you will discover, the causes of most accidents stem from a lack of training, practice or education. We will look at the 10 most common causes of accidents in SCUBA diving, as well as ways to prevent these accidents.

Training

The statement that applies to an untrained CCR diver, "You don't know, what you don't know," is a very good definition of this new adventure. Ignorance is the root of most accidents. Ignorance is not stupidity. It is the behavior and reactions of someone who has not been properly informed and is unaware of critical facts and potential dangers that may result in accidents.

In CCR diving, the only effective path to informed safety is through formal, credible training. Inadequate training is the greatest cause of accidents in CCR diving. Highly experienced OC technical divers have been involved in many CCR accidents. Some people assume that OC trimix divers do not need additional training to safely dive at the same level on a CCR. This has caused fatalities. Almost every emergency management procedure on a CCR is different than on OC, thus every diver needs formalized training at all levels of CCR diving.

Consider yourself a new diver all over again when making the transition to CCR. Learning new skills takes time to retrain the "muscle memory" of your OC mind.

What makes a safe and effective training program? Proper training for rebreather diving not only provides theoretical classroom education, but also dry land, pool and in-water exercises designed to develop the performance of critical skills to the point of reflex action. It also provides the student with a comprehensive knowledge of the demands and dangers of the diving environment, builds safety awareness, emergency preparedness, and teaches divers to control and overcome stress.

Avoid training programs that...

- **Don't provide intense skill development**
- **Push extreme diving without progressive education**
- **Do not provide texts or standardized training materials**
- **Simply provide guided tours**

What to Look For

Seek programs with a proven history of safety and developed by experienced rebreather diving educators. IANTD programs fulfill this requirement. The program must include skills relevant to water safety, stress management, and develop discipline and self-control. It's absolutely essential for rebreather diving. These skills represent realistic circumstances. In addition, simulated emergencies should duplicate problems the CCR diver may encounter. A proper course includes a standard knowledge and skill base through the use of texts materials combined with lectures and in-water performance. Written exams measure a student's knowledge, and in-water skills demonstrate a student's performance level. Penetrations and depth should be achieved in increments under direct supervision of the instructor.

For training to be effective, learning must take place and the certification must be earned, not just paid for. The only way knowledge can be transferred is through communication to a mind that is open, accepting and paying attention! The wise diver thirsts for and digests all the information that can be garnered from the instructor.

Complacency

This is a major concern in rebreather diving. Next to lack of training, this is the greatest contributor to rebreather accidents. It is easy to get complacent on a rebreather because they make diving very easy. This lulls divers into a sense of security that encourages complacency. Always practice basic skills and be vigilant in monitoring your PO_2 and gas supply. Also, stay in touch with your personal feeling of well-being.

These steps help avoid complacency:

1. **Be a thinking diver, not reactionary**
2. **Dive CCR regularly - make it your primary diving equipment (only diving CCR when required leads to decreased reflex skills and familiarity)**
3. **Assume every mechanical/electrical device will fail - practice bailout options periodically**
4. **Assume all emergencies taught during training will happen eventually**
5. **Do not be cheap - change absorbent, sensors and other parts as required**

"Take calculated risks. That is quite different than being rash."

- George S. Patton

Distraction

Distraction is the third contributor to Rebreather accidents. It is easy for a diver to become distracted while setting up a unit or while on a dive. Distraction may be caused by such things as trying to deal with other divers problems while setting a unit up and forgetting to complete portions of the pre dive procedures on ones own unit. Another area of distraction is focusing on others so much that you forget to monitor your own system. Photographers may become distracted by marine life or other photographic situations.

These steps help avoid distraction:

1. **Be disciplined**
2. **Always know your PO_2**
3. **Verify all systems are functional prior to each dive**
4. **Do not dive with a known system failure**
5. **Do not hurry when setting up a CCR - be methodical and thorough**

Gas Management

When using rebreathers gas management procedures are different from those used in OC diving. With rebreathers the diver must plan gas management on the on board gas supply plus bailout gas needs should the diver have to leave the loop and complete the dive on OC.

Planning a Passive SCR dive is the same as OC plus planning of adequate bailout gas requirements to get the diver to the surface on OC, or on a bailout rebreather.

The supply gas duration on a Active SCR is based on the flow rate and gas mixture. Plus, you must plan bailout gas requirements to get the diver to the

Photo by Curt Bowen

surface on OC, or on a bailout rebreather.

On a CCR, the gas supply duration is determined primarily by the oxygen metabolism rate combined with prediction of the amount of diluent gas needed to provide counterlung volume, buoyancy control and dry suit inflation. The diver should return to the surface or a staged oxygen cylinder with 1/3rd of the oxygen supply, plus planning of adequate bailout gas requirements to get the diver to the surface on OC, or on a bailout rebreather.

On all rebreathers the bailout gas should be enough to get 1.5 divers to the surface or other staged dive gases. If diving solo the diver would have to carry adequate volume to get them selves to the surface or other staged gases.

Remember no one has died from carrying too much gas. However, the combined effects of too little gas and failure to manage gas are among the greatest contributors to accidents. If someone recommends that you take a bare minimum gas supply, avoid them. They are a threat to your safety!

Notes:

Exceeding Physiological Limits

This is one of the most dangerous practices in diving. Physiological limits concerning the diver include oxygen exposure, narcosis and decompression risks.

Oxygen limits are a prime concern when divers plan to breathe elevated O_2 mixtures for extended periods during decompression. The rebreather diver must always know the inspired PO_2. Monitor PO_2 on CCR to avoid hypoxia or hyperoxia. The SCR diver should know the inspired PO_2 based on mix and exercise rate. Ideally, the SCR diver will also use a PO_2 monitor.

The effects of narcosis combined with possible CO_2 retention has led industry professionals to recommended that Trimix be used on dives deeper than 120 fsw (36 msw) or even shallower. Another area that has been the source of some controversy in recent years is that of decompression limits. Software programs are available to help divers create custom decompression models. Some divers have created "accelerated" decompression profiles that leave very narrow safety margins.

Decompression is not an exact science. A diver's physiological reactions may vary greatly from dive to dive. The use of extremely "fast" decompression models may place the user at significantly greater risk of injury. To lower risk levels, divers should understand the factors influencing decompression and be appropriately conservative when planning.

Exceeding Risk/Benefit Limits

All divers should respect their personal limits based on their level of training and experience. These limits should include depth, workload, diver fitness, overall degree of risk, difficulty and discomfort the diver is willing to encounter.

Establishing these limits often involves the risk/benefit analysis. When weighing risk against the overall benefit derived from a particular dive, the diver must be certain that what is gained is worth the potential price. Explorers, for example, may often accept a level of risk far greater than that which a recreational or less serious diver would feel comfortable accepting.

Most divers are not willing to accept extreme risk and have no desire to "push the envelope" in hopes of establishing a record-breaking dive. However, there will always be those who will venture where no one else has survived. Without explorers and others who are willing to push the limits in life, we would have no new scientific knowledge or progress as a society.

We should point out the difference between risk taking for the sake of discovery versus risk by knowingly ignoring established safety practices, or by exceeding physiological limits.

When performing a risk/benefit analysis, divers must not only identify all potential risks, but also be able to honestly assess their tolerance for operating outside their normal comfort zone, including the degrees of physical discomfort and mental stress they can endure. When risk/benefit analysis is employed, and all potential risks are identified, the majority of divers will opt for lower risk profiles. It must be understood, however, that risks cannot be eliminated from diving, but merely identified and minimized. All forms of diving encompass risk to one degree or another.

Photo by Curt Bowen

Regardless of your personal risk tolerance, there is no acceptable reason to push air depth limits. Deep air dives expose the diver to the combined effects of oxygen, nitrogen narcosis and carbon dioxide retention. When these physiologically debilitating factors are combined with strenuous work, a dive that is normally within acceptable risk limits may become life threatening. Statistics show that while deep air records may continue to move deeper, the path to these accomplishments is paved with those who did not succeed.

A diver preparing for a high-risk dive must weigh the possibility of death against the gratification of accomplishment. If that price is acceptable then the dive can proceed. But if the risk level is not acceptable, then the dive should not be attempted. Only a fool assumes diving is free of risk.

Risks & Benefits

The aware individual realizes that the more extreme the dive, the greater the price in the form of risk exposure. When creating a risk management profile, divers must identify all variables and potential, "What ifs?" List all potential problem areas, and then provide a proposed solution and outcome for each. Once the list is complete, ask yourself if these risks are acceptable to you.

When exploring new areas, reduce risk by working up to the ultimate goal progressively. Visualization may help solve problems before they happen.

Quitting

It is such a simple word, yet critical to survival or to failure. Dive literature is filled with accounts of trapped or lost divers who spent their last moments of life composing letters to their loved ones. The press and many within the diving community tend to glorify these emotionally charged actions, and the deceased is glorified for the love and concern shown for those left behind.

In many cases, upon recovery it was determined that had the same energy and gas supply been spent attempting to survive rather than stopping to compose a last message, the diver might have reached the surface alive and safe. The impassioned letter is in fact an epitaph to the true cause of death: quitting. A true hero does not quit! This person does survive the seemingly impossible.

Notes:

Unfortunately those divers who do not quit remain a minority, while the majority does not choose overcoming the impossible. While it is not logical that some individuals give up before the end, it is explainable. Many people do not have the training background, experience, confidence, self-discipline, or belief in them needed to confront what seems to be impossible. These persons' deaths are not due to the circumstance but rather to the perception of both the event and their own fragility.

A good training program can help by developing the skill level, discipline and survival attitude that can reduce the probability of quitting. However, it is the individual who must refine his own abilities, develop a strong belief system, continually seek knowledge and fine-tune his own skill level in order to face all of life's challenges.

A positive survival attitude and response comes from within and is produced by belief, confidence, on-going personal training, and learning from the experiences of oneself and others.

Thoughts on Survival

Survival frequently comes down to the ability to focus the mind. A focused mind solves problems. A wise diver will design a custom survival-training program. Survival training programs employ exercises demanding one to go beyond their comfort level. When asked, "Don't you know when to quit?" A survivor responds with an emphatic, "No!" Quitting in an adverse situation leaves only death. Success comes from thinking and reacting accordingly, regardless. Continuing provides the option of survival. Develop discipline to avoid quitting by mental and physical exercise. A focused mind gains control over behavior and physical reactions.

Improper Equipment, Configuration & Failure

You won't have a good dive if you start with "bad" equipment. Sounds obvious, but the record shows that improper, inadequate and poorly maintained equipment have factored into many rebreather diving accidents. For the rebreather diver, their unit is life support equipment, and should be treated as such. Respect the unit as a physiological extension of ones self.

Treat the CCR with the same care and concern as the body. Use equipment you will bet your life on, because you are. Remain open-minded and modify your equipment configuration as better solutions are presented. Do not be fixed and immovable; instead seek perfection.

CCR diving accident records reveal that divers have begun dives with known equipment failures. Many of these were critical; unit would not calibrate, inability to monitor PO_2, low batteries, loop integrity problems, and spent CO_2 absorbent. Obviously these failures have led to hyperoxia, hypoxia and hypercapnia.

Different dive scenarios require different equipment choices - a fact some divers fail to realize when they fall into a "more is better" mind set. Before each dive, select those specific pieces of gear essential to the chosen environment and diving mission. Use redundancy on personal life support items, but avoid unneeded items.

The way in which you configure your selected equipment will also affect the safety of the dive. Hanging gauges, and poorly secured backup lights produce potential entanglement problems, and are more vulnerable to damage. A bailout regulator cannot function if it's clogged with mud, and a back-up light that's been banged against a shipwreck and flooded won't be of much use. Valves need to be easy to reach and the diver needs to intuitively know the purpose of all valves and addition methods.

Avoid gear failure - protect your gear. Secure all equipment to allow for maximum protection and a streamlined profile. Specific mounting techniques are the subject of any quality technical diving course, and remain a topic of study and conversation even among veteran divers.

Failure to select proper equipment or to customize the configuration of that equipment to the diver's specific needs has led to accidents. Do not let something this simple turn you into a statistic.

Dive Team Selection

Although technical diving training programs stress self-reliance and self-sufficiency, these abilities are no substitute for safe competent diving partners. A good dive team is stronger than it's individual members, and can solve problems and prevent accidents. Poorly qualified diving partners or improperly matched dive teams, can create circumstances that lead to accidents. A safe dive team requires hat each team member be competent, responsible, and compatible in skill, experience, attitude and goals.

Accidents happen when highly qualified divers create peer pressure that causes their less-qualified dive partners to exceed personal limits. On other occasions, divers have been known to push a partner beyond their comfort zone and capability for self-control.

Direct ego challenges provoke accidents. This scenario can take place even between friends and couples, often without their awareness. To prevent such occurrences, be aware that not everyone else shares the same capabilities and skills. Similarly, you should recognize your personal limits and not allow your ego or another diver's influence to put you in a situation that is beyond your ability level.

Stress Management

Accidents occur when stress is not managed. Conversely, adept stress management can solve most problems encountered underwater. Managing stress is influenced by training, practice and overall mental toughness. A credible, professional training program includes drills and lectures that enable divers to recognize and cope with stress. A thinking diver is more resistant to stress-induced hazards. Pre-planning and determining answers to "what ifs?" that can occur on a dive can pay off with major benefits in stress prevention. It is this combination of practice and planning that form the foundation for stress management.

Personal Training & Skill Maintenance

As stated in the beginning of this chapter, survival behavior is an ongoing cycle that begins with training, and continues with repetitive practice and skills maintenance. A large number of diving accidents are caused by the divers' failure to maintain or update their skill levels. The maintenance and updating of diving skills is perhaps the single greatest thing that a diver can do to reduce the probability of an accident. Yet, divers who sink into complacency and laziness too often overlook it.

Knowledge, training, attitude, belief in oneself and skill are the keys to personal power.

If you review the cause of accidents, it becomes evident that positive actions will overcome almost any circumstance. Knowledge, training, attitude, belief in oneself, and skill are the keys to personal power. These are all fundamental elements, easily within the grasp of each of us. The application of personal power allows us to keep going, even when the going gets tough. When you apply the concepts discussed in this chapter, you choose to live.

Personal training must be based on a foundation of formal course work, but it goes well beyond the classroom. A prudent diver will always practice and expand upon the basic concepts and tools of the technical diver. Become an expert in the use of these tools.

Conclusion

The key to safety is practice, practice, practice. Be creative and improve the configuration you have developed. Continually review your equipment, and your diving techniques to determine a more efficient and safer way to dive. Be open-minded; do not compromise your own ideals and performance. Strive to perfect your skills and better your preparedness while in the water. You are responsible for your actions, skill, knowledge and fulfillment. Share information and incorporate the knowledge of fellow divers.

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