Motor Skills Learning and Current Bailout Procedures in Recreational Rebreather Diving

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Verdier C., Lee D.R. – 2008 – Motor Skills Learning and Current Bailout Procedures in Recreational Rebreather Diving – Various emergency procedures are used by recreational rebreathers in case they have a complete rebreather failure. Open Circuit bailout ascent proved to be the most common and the safest way to ascend to the surface. However several studies show that a large array of problems can occur. The purpose of the authors is to analyze these elements and the possibility to standardize these procedures.

Keywords: rebreather, hypercapnia, total loop flooding, bailout gas planning, open circuit

Introduction

Bailing out to Open Circuit (OC) is like falling in the snow when you learn skiing. It's a solution when facing a problem. Not always the most elegant solution, but most of the rebreather divers think it's the easiest one and very often the most efficient one.

"If in doubt, bail out!" is definitely the most common advice a rebreather diver can read in the literature. But bailing out is actually much more than simply going off the loop and breathing from a second stage. There are loads of aspects to consider, loads of variable, loads of techniques and regional practices.

Current Practices

A. The reasons to bailout

There is often confusion between breathing on Open Circuit for a few minutes and actually doing a complete ascent on Open Circuit. In the first case, the loop is momentarily unsafe to breathe from (high or low pO2, unknown pO2, etc). In the second case, the rebreather diver considers their loop as definitely unsafe with no hope to recover.

1. A problem that can be fixed.

For example it could be the case if the diver experiences a Hyperoxia or a Hypoxia event. Something doesn't work properly in the oxygen/driving gas injection but with most rebreathers, the diver can override it and fly the unit manually. A few minutes breathing Open Circuit (sanity breaths) will give time to come back to a safe loop content and get a clear head to properly assess the situation and fix the problem ([1]).

Divers using Closed-Circuit Rebreathers (CCR) have developed a large array of techniques to solve most of the mechanical/electronic problems that can occur with their units. Beginners and experienced rebreather divers alike practice skills like Manual Fly (manual O2 injection) or Semi-Closed Rebreather (SCR) mode during and after their training. The goal is to stay "on the loop" as much as possible.

Divers using Semi-Closed Circuit Rebreathers (SCR) have more limited options, especially for the Constant Mass Flow (CMF) models, and the ability to fix the problem underwater is reduced.

2. A problem that cannot be fixed.

Only two main problems can make the loop definitely unsafe to breathe: Total Loop Flooding (TLF) and severe Hypercapnia. In both case, the loop content is compromised and more or less the only option left is to switch to another source of gas to safely ascent to the surface.

2.1. Total Loop Flooding

A partial or complete flood is obviously a very serious problem. Depending on the rebreather design (water, trap, moisture pad, etc), the amount of water and the type of absorbent, several problems can happen simultaneously:
- The rebreather can become very difficult to breathe if some parts of the loop are full of water (counterlung, hose, canister, etc).

- The scrubber material can be soaked with water, making the Work Of Breathing extremely high and even compromising the CO2 absorption ([2]).

- A caustic cocktail can happen from the chemical reaction between water and scrubber material. Divers may experience severe throat and mouth burning ([3]).

- The electronics and/or the O2 sensors can fail or malfunction ([4]).

If a diver properly checks their unit before the dive and maintains the loop integrity during the dive, a Total Loop Flooding is something we shouldn't have to mention. Unfortunately it happens from time to time, mainly because of a user error. In a personal study done with 19 rebreather divers who experienced some forms of Loop Flooding ([5]), the authors found that:

- 63% of them made a mistake with their mouthpiece (mouthpiece kicked out or removed underwater while still open, etc).
- 31% had an equipment problem that could have been spotted by a proper pre-dive positive and negative pressure test (defective O-ring on the canister, manual injector unscrewed, improperly fitted hose connection, etc).
- 6% had a puncture in the loop while penetrating a wreck.

Only 26% of these loop flooding were severe enough to initiate a complete OC ascent. In the other cases of this study, the amount of water wasn't significant enough, or the rebreather design allowed the divers to effectively drain this water out of the loop.
However, regardless of the severity of the loop flooding, this study shown that most of these problems were related to:
- *An improper or a lack of Loop Integrity Test before the dive*. The well known Positive and Negative Pressure Tests should be perform anytime after a component of the breathing loop has been removed and replaced (canister lid open to check the scrubber or the electronics, ADV or manual injector removed to drain some water, etc).
- *The lack of a neck strap or a Full-Face Mask* that could obviously help avoiding any accidental loss of the DSV.

2.2. Hypercapnia

Hypercapnia being a real concern in rebreather diving, it would be a safe attitude to treat the CO2 absorption process with the utmost precaution.

There are several ways to increase the inspired CO2:
- *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 engine.

- *By failure of the absorbent system*. Many things can contribute to this situation ([6]):

- Used CO2 scrubber material or inability of the material to absorb CO2 (cold water, deeper depth, improper granule size).
- Channelling in the scrubber.
- Contamination of the scrubber material with water.
- Critical O-ring failure in the loop, allowing the used gases to by-pass the scrubber.
- One-way valve failure, preventing the gas to go to the scrubber.
- Use of an improper Full-Face Mask (CO2 build-up inside the mask).

- *By incomplete elimination of the CO2 produced in the body*. This can happen if:

- One breathes very rapidly, but takes only very small shallow breaths. In this case, no gas is actually moved into the alveoli. Therefore CO2 is not eliminated.
- One voluntarily slows down their breathing pattern in order to "save gas" on open circuit (hypoventilation or skip-breathing).
- One doesn't breathe faster when the pCO2 rises in the blood. This normal response of the respiratory system is sometimes impaired in people called "CO2 retainers" (some studies show that there seem to be more CO2 retainers among divers than in the general population) ([7])([8]). It also

seems that Respiratory Muscle Training can normalize low CO_2 sensitivity ([9]).

- The work of breathing is increased. 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 (sub-standard rebreather design, small scrubber material granules, higher density of the inspired gas at depth, tight diving suit and harness, etc) ([10]).

Signs and symptoms of hypercapnia may include cottonmouth feeling, warmer ambient/loop temperature, elevated breathing, stress, dizziness, tunnel vision and limb weakness. Hypercapnia also enhances Nitrogen Narcosis and risks of Oxygen Toxicity ([11]). In its most severe form, it can also trigger unconsciousness ([12]). Anecdotal evidences show that the symptoms might be so severe that chances to recover from the CO_2 hit become minimal ([13]) and keeping on breathing from the loop (even on an SCR mode) makes these chances even smaller ([14]).

Unfortunately a rebreather user survey relates some experiences of hypercapnia and the inability for the divers to control what they are actually doing: "*I was not able to remove the mouthpiece for a bail out, as I was not able to hold my breath long enough for the swap over*". Another diver relates: "*Very rapid breathing rate was uncontrollable. Felt like I just could not get gas in fast enough and nearly had to hold the mouthpiece in my mouth to make sure I didn't blow it out of my mouth during exhale*" ([15]).

B. Current reactions to an emergency

Different techniques are used in the rebreather diving community, when dealing with most of the problems that could occur with a rebreather (equipment failure, physiological problem, etc).

- *Diluent flush*. Taught by most of the training agencies, this technique helps making sure the loop contains a safe gas, at least for a few seconds ([16]). Four or five breaths should help most of the divers experiencing any kind of mild symptoms to quickly regain their ability to think properly and to react in the most efficient way. In case of hyperoxia, hypoxia, mild hypercapnia, or any mechanical or electronic problem, a proper diluent flush can help. Even if this doesn't help, most of the time it doesn't make any harm if the mix is safe to breathe at that depth, apart from depleting the stock of gas available. However this technique only momentarily provides a safe breathing mix but doesn't necessarily fix the problem at the origin of the situation.

- *Open Loop Technique*: This technique is only possible with CCRs with an Automatic Diluent Valve (ADV). In this case, the diver can use the ADV as a kind of "manual 2nd stage". The diver activates the ADV every time they want to inhale. Exhalation is done through the nose to provide the same benefits than a standard OC second stage. This technique can be done almost immediately but is obviously not very convenient in case of a flooded loop ([17])([18]).

- *Combined inflator/2nd stage*. Some rebreathers like the APD Inspiration and the Evolution CCRs come standard with a Low Pressure Inflator (LPI) combined with a small 2nd stage. It gives the diver the option to have a compact regulator already connected to the on-board gas, conveniently stored on their chest or around the neck ([19]). However some rebreather divers have reported that they are difficult to breathe at depth, or might leak when fitted on a Trimix mixture.

- *Standard 2nd stage*. Fitted on a sling tank or on the on-board gas, it provides the diver with a sufficient and known source of gas. Equipment configurations might vary quite a lot:

- Some divers store one or several 2nd stages (depending on the number of tanks available and their personal preferences) on a shock cord loop around the neck or clipped on a D-ring on their chest.
- Some divers stores the complete regulator on the side of the sling tank, tucked under some form of bungee loops.
- Other divers use 5 to 7ft long hose regulators giving them the flexibility to help an out-of-gas diver without unclipping any tank.
- Divers using some models of Full-Face Masks might also have this

second stage already fitted on side of the mask ([20]).

- As a last resort solution, out-of-gas divers can also rely on their teammate to provide some gas. In very shallow water, a controlled swimming ascent has also been used in some emergencies.

- *Bail-Out Valve* (BOV). A BOV combines the rebreather Dive-Surface Valve (DSV) and an emergency 2nd stage in the same mouthpiece. With a BOV the diver is able to immediately switch from their rebreather loop to a known breathing gas on Open Circuit. This helps to reduce the stress level, as the BOV is already in the mouth so no delay, less risk of drowning or panic. Additionally another diver can help the affected buddy and switch the BOV to the OC position. However the authors found a large number of equipment configurations where the BOV is connected to the on-board diluent (CCR), a sling tank or even both, thanks to various manifolds, quick-connects and swivels. Divers have also to be aware of the mix being supplied, the BOV being sometimes connected to a Trimix mixture that is hypoxic at or near the surface.
Some BOVs are available standard with some commercially available rebreathers, but most of time as stand-alone accessories with adapters to fit in all the major rebreathers currently available. A proper BOV should ideally be ([17]):

- *Small and light*. No one wants to have a small anvil hanging from their mouth. It would be at least uncomfortable, even dangerous, as it will increase the risks to loose it and flood the loop.
- *Easy to switch*. Some BOVs are very stiff and one needs the help of a team of weightlifters to operate the lever. Not the best solution when the loop is full of water and the diver's lungs empty since a few minutes.
- *Easy to breathe at depth*. When a diver needs to breathe OC, it's because they NEED to breathe! Only high performance 2nd stage should be used in BOVs. Even if the diluent mix might be easier to breathe because of its Helium content, the fact is that one needs a lot of gas when switching to OC. A hard-to-breathe-at-depth BOV will just make everything worse and increase the stress level ([21]).
- *Not free flowing*. That's where manufacturers speak about compromise. How could an easy-to-breathe 2nd stage will not be prone to free flow (at the surface when submerging, or when scootering)? One answer is the adjustable knob, designed to avoid loosing the so precious and limited gas at the beginning of the dive. It should be set "Hard" before jumping into the water, then loosen up during the bottom phase, just in case…
- *Air and watertight*. That's where some of the BOVs on the market have a lot of problems. Personal experience had shown a lot of leaks and failures to hold negative pressure with several BOVs that come standard with some popular CCRs. It's life-support equipment so proper designing and machining are of the utmost importance.

- *Bail-Out Rebreather (BOB)*. A second rebreather could be an interesting alternative to the OC bailout way. Rather than carrying a lot of tanks in case of deep/long rebreather dive, a BOB helps in keeping the tanks as small as possible. Some manufacturers start to explore this option but the liability/safety issue and the small size of the market don't really help to speed up the designing process. A properly functioning rebreather provides the diver with the ability to complete their dive with a similar gear that the one they started with. However different configurations are available (twin-rebreathers, sidemount rebreather, chest-mounted rebreather), some of them leaving no possibility to help another diver in need of gas ([22]).
Some experiments also show that, even if a diver has a bailout rebreather, they still need a small amount of open circuit gas at least to clear the head, rest and properly think, before being able to start the emergency ascent. In case of severe hypercapnia, it can take a while on Open Circuit before the diver accepts to switch to a "cold loop" (unused bailout rebreather scrubber, the chemical reaction needing heat to take place) ([14]).

- *Multiple bailout tanks.* Here again, no real standard seems to exist in the rebreather diving community. Some divers simply carry more or less the same tank, whatever the dive they do. Or if they carry multiple tanks, they try to sling them more or less everywhere on their body: a small one on the top of the rebreather, a small one clipped on their waist strap or along their rebreather, a big cylinder slung on each side. However several options are popular in the rebreather diving community:

- *Sling tanks on the left side*: it frees up the right side (easy access to the right thigh pocket, easy operation of a scooter), but the diver is only balanced if using Aluminum tanks and having a canister light on the right side ([23]).
- *Sling tanks on both sides*: It gives a better balance with steel tanks (except with an Helium-based mix) and decreases the risk of confusion for a gas switch (O2 rich tank is on the right hand side). However both sides are cumbered and it becomes difficult to access both pockets and both OTS counterlungs. With a canister light cable and the long hose, the risk of entanglement is clearly higher.
- *Stage tanks*: in a controlled environment, bailout tanks can be staged (cave) or clipped on a shotline (wreck) if the divers are 100% sure to find them back when needed ([24]). It saves a lot of work in carrying tanks but divers have to take all measures to be able to find the tanks in case of emergency (reel to the shotline, tanks clipped on the guideline in a cave, etc) ([25]).
- *Team approach*: Some realize that they might need a lot of gas to safely ascend to the surface. Several Training Agencies and rebreather divers groups suggest to share the bailout gas between the members of a team, assuming that team members will stay together at all time, and that only one diver will have to bailout. The rule then is still to have ample reserve of bailout gas ([1]).
- *Alpinist approach*: based on their experience, some rebreather divers simply choose not to take that gas, and just trust the statistics: divers never use that gas anyway! ([26]) This opinion obviously needs a strong trust in the rebreather (thorough checklist and maintenance schedule) and the diver's ability to deal with any situation without OC gas (training, experience, skills, etc).

C. Potential Problems during the ascent

All rebreather divers (either SCR or CCR) learns during their basic rebreather diver course that having enough open circuit gas to safely ascend to the surface is not an option. It's a requirement ([25]).

Why going the OC way when there are so many other options with a CCR? Because it's safe! If a diver doesn't know where does the problem come from, if they don't know how to fix the problem, or if they simply don't know if the mix in the loop is breathable, the Open Circuit ascent to the surface is a commonly accepted solution in the rebreather diving community.

Ascending from a few metres/feet to the surface while breathing from any of the option above (BOV, Open Loop, combined LPI/regulator, etc) is usually not a real problem for most of the divers. When ascending on open circuit from depth though, anecdotal evidences show that in real life situations, a few problems usually happen. This is especially true for deep/Trimix dives when the decompression burden is important and where additional factors might increase the risks (Narcosis, risks of DCS, cold water, etc).

Problems can be very different depending on the environment, the rebreather being used and individual factors. However experience has shown that the most common ones are ([27]):

- *Task loading*. The diver has many things to do to prepare their OC ascent:

- Switching to their bailout mix (noise and bubbles can increase an already rising stress level).
- Communicating with their teammates.
- Assessing the environment and how to safely ascent (swimming back to a shotline, doing a free ascent, using an SMB, etc).
- Preparing for a proper decompression. Divers can use bailout OC tables they carry with them, or switch their dive computer to OC mode (a time-consuming operation for many divers).

- *Time pressure*. As soon as a diver switches to open circuit, the gas consumption will deplete the bailout tanks quite rapidly. Anecdotal evidences have shown that divers have usually a higher RMV on Trimix than on air and the stress level caused by an emergency ascent can drastically increase it ([28]).

- *Equipment Problems*. Many pieces of equipment can bother a diver during an OC ascent and therefore compromise their safety:

- Breathing loop: most of the time, a breathing loop is not designed to stay out of the mouth. It's either floating just in front of the diver's face (impairing the communication with the other divers) or extremely uncomfortable if kept under the bailout regulator.
- Regulator: low-performance, hard-to-breather-at-depth regulator increases the Work of Breathing and the stress level in an already distressed diver. A diver, who just experienced some form of hypercapnia or a high level of stress at depth, needs a lot of gas.
- Complex cluttered gear configuration: extensive studies have been done by several groups of technical divers. A stressed diver might find difficult to deal with multiple tasks. Simple things like switching to decompression mix might become a challenge when the tanks are not clearly marked to avoid confusion and their regulator not stored in an accessible way.

- *Environmental conditions*. Having to fight against an unexpected current during the emergency ascent or loosing the teammates because of a poor visibility are all stress factors. Breathing open circuit is also a contributing factor to hypothermia, compared to breathing on a rebreather, further increasing the gas consumption ([29]).

- *Buoyancy control*. Here is the most important part: dealing with an expanding loop while ascending.

- The Over-Pressure Valve (OPV) is sometimes not efficient enough to vent the loop, depending on its location on the rebreather.
- The Gas Injection System might further impair buoyancy control (constant leak on mCCR et CMF SCR, solenoid O2 injection on eCCR). Any gas injection during the ascent will make the diver's life miserable in the shallows.
- Buoyancy Compensator and dry suit have to be vented during the ascent, further increasing task loading in the shallows.

- *Proper Weighting*. Many rebreather divers are properly weighted for normal diving circumstances, with their bailout tank full. It's quite fine for 99% of their dive but if all of a sudden they have to breathe from these tanks, they might end up in a difficult situation. When almost empty the bailout tanks become increasingly buoyant, making quite difficult to maintain depth control during the stop. Same problem if they have to pass the tanks to another diver. Divers should always make sure that they can maintain their depth with and without their sling tank(s), would they be full or empty ([30]).

- *Stock of gas*. Here again many rebreather divers might have some bad surprises when dealing with a real emergency. Respiratory Minute Volume (RMV) becomes ballistic at depth with stress. Stressed and task-loaded divers can easily double their normal gas consumption on open circuit ([31]). And watching the needle of a pressure gauge steadily going down toward the red zone doesn't help to relax. Fighting to control buoyancy neither. Many divers just use their decompression softwares to plan everything for them, from the mixes they will use to the gas they will carry. Most of the deco softwares use one or two different SAC (Surface Air Consumption) rate to compute the gas usage during the dive ([32]). Unfortunately the bottom/deco SAC rates don't always work. Deco softwares assume the diver sticks to this SAC rates but it's not always the case, as one might have to swim hard or fight against a current on the bottom or during deco.
Not enough gas and the diver obviously can't deal with the emergency. As the brain understands that there is a possibility that the diver will not make it to the surface, the stress level increases, along with the breathing rate.
Too much gas and the diver feels confident in their ability to cope with any problem that could occur during the dive. But this comes at a price: carrying big bailout tanks that will not be used during 99.9% of the dives. Even if carrying a LOT of gas sounds like a safe option, there are also some limits:

- Sling/additional tanks are bulky and don't help to streamline the equipment, increasing drag and gas consumption.

- The diver is heavier, as they can't remove any weight from the weight system. A diver is supposed to be neutrally buoyant without the bailout tanks. So the weight to carry underwater and at the surface will be impressive.
- Additional tanks mean more regulators, more drag and more entanglement hazards.

- *Bailout Mix(es):* Improper bailout mix selection on open Circuit can lead to many problems like Inert-gas narcosis, hypercapnia, Oxygen toxicity, Decompression Sickness (DCS) and Isobaric Counter-Diffusion (ICD). Most of these problems are enhanced by stress and incomplete elimination of the CO2. The mixes being used by one diver can even be different from the ones being used by the other divers within the same team, making any gas sharing even more complicated.

Discussion

Regardless of the situation, the equipment and the environment, it has been proved that an individual better handles stressful situations if they can apply a standard pattern (reaction behaviour). Even with situations as different as emergencies with a rebreather underwater, the procedures should always follow the same initial path, in order to keep the thinking process as limited as possible. When someone's brain becomes as small as a peanut and as primitive as an action movie hero, one needs simple steps to follow. The strategy relies on the training of certain patterns of behavior, which are supposed to keep the individual safe in stressful situations ([33]).

The main questions when planning for a bailout ascent are:

- Which mix(es) to breathe?
- How much gas to carry?
- How to carry it?
- How to safely ascend?

1. Appropriate mix

The bailout mix(es) should meet the following requirements:
- *Safe to breathe*. The mix should obviously not be hypoxic or hyperoxic in the depth range where the diver might use it. Proper marking of the Maximum Operating Depth (MOD) is of paramount importance.
- *Easy to use*. Experience shows that using the same bailout gas than the on-board diluent gives more flexibility. If the diver runs out of on-board diluent, most of the rebreathers allow the diver to plug in the off-board tank.
- Easy to breathe. If the choice is between Air, Nitrox and Trimix, it's definitely better to switch to a Helium-based mixture, as it's lighter to breathe. The lower WOB then helps the diver to recover from a severe hypercapnia.
In order to calculate the density of a mixture, the only thing to do is to multiply each gas percentage by the density and the total pressure ([34]).

Gas	Density
N2	1.2498
O2	1.4276
He	0.1785
Ar	1.7819

Fig. 1: Density of various breathing gases ([35])

For example, Trimix 10/70 is made of 10%O2, 70%He and 20%N2. At a depth of 70m / 230ft, the ambient pressure is 8 ATA.

The density of this mix (Tx10/70) is:
(0.10 x 1.4276 + 0.70x 0.1785 + 0.20 x 1.2498) x 8
= 0.517 x 8
= 4.141

The density of air is:
(0.21 x 1.4276 + 0.78 x 1.2498 + 0.01 x 1.7819) x 8
= 1.292 x 8
= 10.339

At 70m / 230ft, air is therefore almost 2.5 times denser than Trimix 10/70. It seems logical that this Trimix will be easier to breathe than air. The WOB will be lower.

As a matter of fact, the density of this Trimix at 70m / 230ft should be comparable to breathing air at:
4.141 / 1.292 = 3.2 ATA or 22m / 72ft

2. Sufficient Gas

The literature is quite prolific about gas planning for Open Circuit Divers, not about Rebreather Bailout gas Planning. "The diver should take enough gas to ascend and decompress" ([24]) seems to be the rule usually followed. But "*How much gas does a diver actually need?"* is a tricky question as different situations ask for slightly different rules. However experience shows that: "one has never enough gas, as breathing rate is always higher than planned". Decompression Softwares are useful tools but sometimes don't have enough flexibility for complex emergency bailout gas planning.

2.1. Open water NDL recreational dives

Simple rule of Thirds: when there is a direct access to the surface at all time, and no need to come back to a shotline or a specific entry/exit point. The necessary gas volume to ascent is then simply multiplied by 1.5 to allow for some additional reserve ([1]).

Sufficient gas = ascent gas x 1.5

Many rebreather divers plan their dive using Surface Air Consumption (SAC) rate of 30 L/min / 1 cuft/min as it quite reflects what rebreather divers can actually breathe when going Open Circuit. It's much higher than the usual SAC rate because of the stressful situation at the origin of the bailout situation (flooded loop, CO2 hit, etc). However a much higher SAC rate becomes unrealistic, as most of the people can't really sustain it for more than a couple of minutes. Even in a very stressful situation, the diver will calm down during the ascent (deco) but the SAC rate calculation will still keep the same figures, averaging up a temporary higher SAC rate on the bottom ([36]).

The SAC rate has always to be multiplied by the ambient pressure (in ATA).

For the ascent portion, it is easier and faster (but still quite accurate) to use the average depth and the ascent time (1 minute for each 9m / 30ft) ([37]):

Av. dpth = max depth - [(max depth + min depth) / 2]

Minimum depth will be the surface for a No-deco dive, or the depth of the 1st stop for a deco dive. A safety stop is always recommended. This can be done on the bailout tank or using the on-board O2.

So for a No-Deco dive at 20m / 65ft, the sufficient gas is:

30L/min x 2min x 3ATA x 1.5 = 270L of gas

2.2. Open water decompression dives

Rock Bottom: when an additional safety factor is desirable and when decompression stops are planned, one can add a couple of additional minutes at maximum depth (emergency gas).

Sufficient gas = (emergency gas + ascent gas + deco gas) x 1.5

Bailout planning should be done on a worst-case scenario basis, assuming that the problem occurs at the worst possible moment on a decompression standpoint: the very last minute of the bottom phase. Therefore bailout gas planning will take into account the maximum OC decompression profile one might have to do ([38]).

For a 20min deco dive at 50m / 164ft, the sufficient bailout gas would be:

- Emergency gas (at the bottom):
30L/min x 2min x 6ATA = 360L of Tx18/45
- Ascent gas (to the 1st stop at 21m / 70ft for this example):
30L/min x 3min x 4.5ATA = 405L of Tx18/45
- Deco gas (for all the stops):
30L/min x 1min x 3.1ATA = 93L of Nx50
30L/min x 1min x 2.8ATA = 84L of Nx50
30L/min x 1min x 2.5ATA = 75L of Nx50
30L/min x 1min x 2.2ATA = 66L of Nx50
30L/min x 3min x 1.9ATA = 171L of Nx50
30L/min x 14min x 1.6ATA = 672L of Nx50

Sufficient gas is:
(360L + 405L) x 1.5 = 1148L of Tx18/45
(93L + 84L + 75L + 66L + 171L + 672L) x 1.5 = 1742L of Nx50

2.3. Overhead environment dives

Penetration rule: when one part of the dive or the whole dive has to be planned with a specific exit point, rebreather divers mainly add a couple of additional minutes at the furthest point of penetration (emergency gas). They normally use the Rule of Thirds for each and every mix being used. However the Rule of Fourth (where the gas volume is multiplied by 2) has proved to be more realistic and safer for the penetration part of the dive, in order to deal with additional delay to exit (silt-up situation, entanglement, restriction, current, light failure navigation error, etc) ([39]). Some cave divers also calculate their bailout gas in "litre / metre of penetration" (assuming constant swimming speed and average depth). Cave rebreather divers have been reported to use the Rule of Fifth when exit can be delayed even more (i.e. scooter failure).

In some caves, the decompression stops might have to be performed inside the cave, as well as the main part of the ascent. In this case, the Rule of Fourth might apply as well for Ascent gas and Deco gas calculations. Otherwise, the gas calculation is:

Sufficient gas = (emergency gas + exit gas) x 2 + (ascent gas + deco gas) x 1.5

For a 20 minute penetration dive (cave or wreck) with the entrance at 20m / 65ft (average depth: 30m / 98ft):

- Emergency gas (at the bottom):
30L/min x 2min x 4ATA = 240L of Nx32

- Exit gas (to go out of the overhead environment):
30L/min x 20min x 4ATA = 2400L of Nx32
- Ascent gas (to reach the 1st stop at 9m / 30ft for this example):
30L/min x 1min x 2.5ATA = 75L of Nx50
- Deco gas (for all the stops):
30L/min x 6min x 1.9ATA = 342L of Nx50
30L/min x 27min x 1.6ATA = 1296L of Nx50

Sufficient gas is:
(240L + 2400L) x 2 = 5280L of Nx32
(75L + 342L + 1296L) x 1.5 = 1713L of Nx50

3. Safe Emergency Reaction

As a word of caution, if a rebreather diver happens to think about bailing out to Open Circuit and doesn't even know why, they should never hesitate a split second to go OC because that might be their last chance to do so.

Having a standard "reaction pattern" can quickly help to keep the situation under control. It has been shown that decision-making process is greatly impaired by stress in an emergency situation ([40]). In order to find the proper behavior, the diver has to be able to focus on information gathering based on their experience, rather than focusing on the immediate course of action ([33]). Therefore for any loop-related problem (hypoxia, hyperoxia, hypercapnia, loop flooding, electronics failure):

1st STEP: LOOP FLUSH

Whatever the type of rebreather being used, a good loop flush will guarantee at least for a few seconds, a proper mix in the loop. Enough time to go to the bailout regulator for the next step ([20]). This step is obviously less important with a BOV or in case of caustic cocktail.

2nd STEP: SANITY BREATHS

Switching to Open Circuit and taking a few breaths of a known source of uncontaminated gas is sound advice, just to get a clear head and evaluate the situation. Hypoxia could quickly lead to unconsciousness, as does Hyperoxia. Carbon Dioxide can hinder cognitive processes (however, switching to open circuit does not always immediately alleviate the symptoms of severe hypercapnia) ([10]). A proper BOV is a desirable safety item to quickly and safely perform the sanity breaths.

3rd STEP: PROBLEM IDENTIFICATION

It's now time to understand what the problem really is. Some diagnosis tools are available, depending on the type of rebreather. On a CCR they are:

A. **pO2 readings** (handset, HUD, audible alarms). After a loop flush, the sensors should read the proper pO2 related to the depth. Therefore their behaviour should help to understand if the problem is related to the electronics or to the gas supply.
B. **Tank Pressures**. A quick glance on the in-board and off-board tanks can help to determine if it's a problem with the gas supply. More important; it can also help the diver to decide if they have enough OC gas to try to fix the problem at depth or if the ascent (or the return to the exit) has to be started immediately.
C. **Noise and bubbles**. The noise (or the lack of noise in case of a solenoid stuck closed) could help to locate a leak in the loop or the gas supply.
D. **Symptoms and feelings**. The diver should also take the time (a few seconds) to listen to their body. Any unusual symptom (light head, vertigo, laboured breathing, etc) should be compared to the first evaluation of the situation in order to confirm or not the diagnosis.

4th STEP: CORRECTIVE ACTION

There are only two options, depending on the problem, the state of the diver, the type of rebreather, the logistics and the decompression obligation. The Decision-Making process is made easier by following the 3 previous steps:

A. **Problems Solving**. The diver may decide to go back on the loop if it's possible to solve the problem and keep on breathing a safe mix. For instance, an Electronic Closed-circuit rebreather (eCCR) can be flied manually or can even be used as a manual Semi-Closed Rebreather.

B. **Bailout ascent**. If the problem can't be fixed, it's the time to prepare the ascent. Divers should never completely drain their on-board gas as most of the time, it's also the gas used to inflate the Buoyancy Compensator, a useful tool to control buoyancy at depth or to become positively buoyant at the surface. So it makes sense to switch over to a completely separated gas supply (usually sling tanks or staged tanks in a controlled environment).

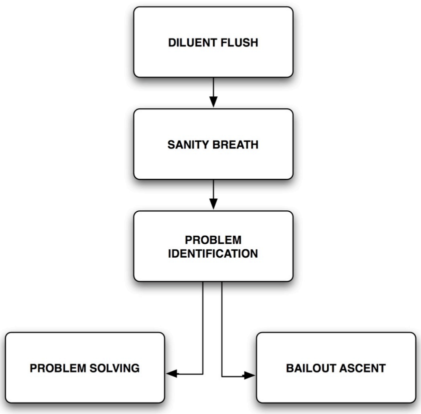

Fig 2. Reaction to an Emergency

4. Safe Bailout Ascent

Because of the various problems rebreather divers might experience when they do an emergency ascent on their Open Circuit Bailout gas, the course of action needs to have some priorities. The following actions are valid for open water diving, when the ascent is not delayed by any actual ceiling at depth (cave or wreck penetration). The goal is to keep the ascent as simple and hassle-free as possible, to avoid unnecessary stress ([27]) and delay:

- *Team Communication*: essential as it avoids separation and provides the distressed diver with additional resources (gas, light, SMB, brain…).

- *Immediate ascent*: it reduces the ambient pressure, the pO2 and the pCO2. It also lowers the gas consumption and the inert gas uptake, actually allowing the body to off-gas.

- *Decompression Planning*: during the beginning of the ascent, the diver can take their OC Bailout tables or switch their dive computer to OC mode. Computer switch takes time, so it might be simpler if the bailout bottom mix is the same that the on-board diluent/driving gas being used, reducing the operations to do on the dive computer.

- *Buoyancy and ascent rate control*: For mCCR and SCR, the tank valve should be closed to avoid constant gas leak in the breathing loop. With an eCCR (if the electronics is still properly functioning), the diver has also the option to select a low setpoint. Loop, Wing and dry suit have to be vented frequently (the diver might also have to find the proper position with the overpressure valve as the highest point. On some rebreathers, the OPV is located on the bottom of the exhalation counterlung and it might be convenient to unclip the bottom of this counterlung to help to vent its content. An SMB also helps by providing a visual reference for the ascent.

- *Decompression and gas switch* (if appropriate): Divers performing emergency ascents have always shown some signs of stress. Because of that, they should apply extreme care when decompression stops have to be performed. Also confusion can happen when the diver has to switch to a decompression gas. All these actions should be carefully monitored by a teammate, as risks of a mistake are higher than usual.

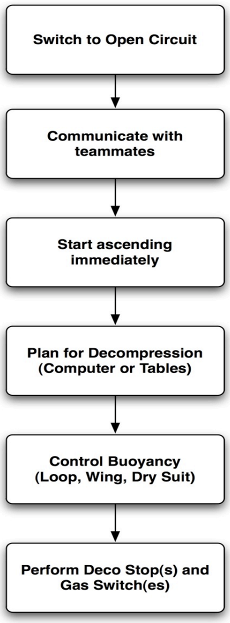

Fig 3. Bailout Ascent

Conclusion

Based on the various aspects of an emergency situation and the large array of problems a distressed diver can encounter in case of total rebreather failure, the author's recommendation is to simplify and standardize the procedures being taught to the rebreather divers. Task loading and stress can lead to more complex and dangerous situations. It is of the utmost importance to teach how to make the equipment configuration as emergency-friendly as possible and how to prioritize the actions to be taken for a safe ascent. The authors would like to see further studies being done about bailout rebreathers, and other pieces of equipment like Full-Face Mask.

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