



## **A SURVIVAL GUIDE TO REBREATHER DIVING**

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### **PART 1: CONSIDERING REBREATHER DIVING - KEEP ON CONSIDERING**

#### **Introduction**

Re-circulating self contained underwater breathing apparatus (rebreathers) are wonderful devices. Once almost exclusively used by the military, since their introduction into sport diving, rebreathers have opened up a new world of possibilities to the sport and scientific diving communities; incredible exploration has resulted and today, dive sites that were once well beyond the capability of the averagely equipped and trained sport diver are now a routine weekend dive for an increasing number of us. However entry into this new world comes at a cost, the penultimate price I believe being your demise. I say penultimate because what I consider to be the ultimate price will be discussed later.

The once 'cottage industry' of sport rebreather manufacturing is maturing, the importance and significance of design standards, third party independent testing, production quality assurance and appropriate training is now at the forefront of diving industry discussion and progression. As a result, the 'bar' on these issues continues to be raised and long may it continue to, after all, we're talking about life support equipment. However, despite best practice in engineering design, testing, production and training, rebreathers remain complex systems that given the opportunity, can quietly and unknowingly incapacitate a diver, often resulting in a fatal outcome. Rebreather self preservation is a survival state of mind I adopt and try to instil in all my students. Do not blindly trust your rebreather to sustain your life, it's not always going to. With over two-decades of rebreather diving now behind me, much of which has been spent in rebreather development, testing, production and training, I offer here for your consideration some personal thoughts and opinions on surviving rebreather diving.

#### **Rebreathers Are Not Suited To All Diving and All Divers**

The first and obvious means of surviving rebreather diving is not to use one. Whilst exact statistics are vague, there is credible evidence to suggest you are significantly more likely to lose your life diving whilst using a rebreather compared to open circuit SCUBA. If you are considering rebreather diving, ask yourself do you need a rebreather and if so why. Consider a rebreather a 'mission specific tool' ideally suited to particular applications where the various merits of rebreathers can be exploited. However rebreathers are not necessarily the ideal choice for general sport diving where a risk / reward imbalance likely exists.

Buying a rebreather is a significant personal investment, the initial financial outlay is very high and through life costs can be considerable. Unless you are an avid open circuit mixed gas diver exhaling thousands of litres of expensive helium and oxygen into the water each month, you are unlikely to ever re-coup the costs of purchasing and using a rebreather. There is nothing like the convenience of using open circuit SCUBA for a 'routine' recreational dive. If extended duration, cave, deep wreck or mixed gas diving does not make up the majority of your diving activity, considering all the associated cost, logistics, pre / post dive preparation, maintenance and risk increase, ask yourself whether a rebreather is the appropriate life support system for you.

Commercial forces are driving rebreather use by the wider diving community via the advent of the so called recreational rebreather or rCCR. Despite a detailed Human Error Analysis (HEA) and resulting life support design enhancements to mitigate the errors identified, rebreather use will always present significant opportunity for complacency or incorrect action, the consequences of which can be deadly. Looking beyond the rCCR marketing hype, it is important to acknowledge that rebreathers are not suited to all divers, many of whom simply lack the personal discipline, attention to detail, patience and aptitude to consistently use them in a safe manner. If you are not a self disciplined

individual who frequently dives, thus maintaining a basic level of in-water competency, consider whether a rebreather is really for you.

### **Make a Considered Choice**

If you are committed to purchasing a rebreather, think very carefully about which rebreather to buy. There is no perfect solution, to enable a person to breathe from a self-contained re-circulating underwater breathing apparatus requires certain human factor compromises. Each rebreather design therefore has its weaknesses and strengths.

Different manufacturers place different priorities on particular design characteristics, i.e. oxygen partial pressure management, counter-lung position, CO<sub>2</sub> monitoring, weight, dimensions, etc, therefore research the subject thoroughly. However, if you have no experience or a limited understanding of rebreather technology, researching a subject from a limited knowledge base presents a challenge to the decision making process and encourages the emergence of a certain human weakness and the salesman's best friend: impulse buying. Try and fight off any impulse to buy a particular rebreather and do not blindly trust marketing literature, forum chat room discussion or manufacture representatives.

With a low knowledge base, it is easy to be persuaded that a particular rebreather has superior performance or advantages when compared to another. Therefore consider carefully your options, take opportunities to participate in 'try dives' to experience yourself the fit, form and function of as many different rebreathers as possible. When you have down selected, before you place your order, self check your decision, clarify in your own mind the reasons why you are considering this rebreather.

Be a thinking rebreather diver. Don't just follow popular trends, which by definition are fashions that appeal to groups with similar tastes or to those who wish to conform. A fashion ceases to be so very quickly and the world of rebreathers is no different. You only need look at what has and has not been fashionable in rebreather market over the last decade. Follow a trend only if the reasons for doing so are based upon rational considerations driven principally by your safety. Study the merits of each rebreather design. This can be difficult if you've limited rebreather experience, particularly when an increasing number of novel designs are appearing on the market. However, it's important to look beyond any novelty factor or 'sophisticated' feature when assessing a rebreather, instead remain with fundamental life sustaining design considerations, because when it fails, and it will, these fundamental design features will enhance the likelihood of surviving. Key design safety characteristics to look for are:

- Minimum resistive effort and static lung-load under empirical test conditions
- Oxygen sensor moisture management
- Water ingress management in event of a partial flood (where is the water retained within the loop and/or what means of water blockage is employed to limit water migration within the electrical system)
- PO<sub>2</sub> control and a redundant means of independent PO<sub>2</sub> monitoring
- Canister performance under empirical test conditions
- Software third party validation
- Environmental testing under empirical test conditions
- Electro magnetic shielding from external radio frequency influences - validated under empirical test conditions
- Build quality and material selection
- Robust O ring seal design, in particular on components that are frequently disassembled, i.e. canister and breathing loop components.

Also consider that the most technically sophisticated option need not necessarily be the safest option; the more complex the engineering the greater the potential number of failure modes that may be inherent within the design. There is a strong case for 'less is

best' and it is not uncommon to be sat next to persons on a dive boat who cannot, or should not dive because their 'sophisticated' rebreather has developed a fault.

## **PART 2: EDUCATION AND CERTIFICATION, UNDERSTAND THE DIFFERENCE**

### **Choose Your Instructor Carefully**

Rebreather training curriculums and standards do not differ significantly between training agencies. They are all trying to achieve the same objective, i.e. an appropriately trained rebreather diver within a short a period as they each deem safely possible. I do note however a large variance in the quality of Instructor / student training materials, some of which is woefully inadequate and greatly deminishes the overall quality and delivery of the training package. Despite this though, in the main, rebreather instruction comes down to the quality of the individual Instructor and not the agency under which he / she instructs. Unfortunately the rebreather training market is awash with instructor mediocrity, review <http://www.hse.gov.uk/diving/video/co2video.htm> as an example of how incorrect instruction can go badly wrong.

Dilution of training quality is the inevitable consequence of the way the rebreather market has developed over the last decade, holding a rebreather instructor certification card does not necessarily correlate with high quality instruction. Again do your research, good instructors who also have extensive rebreather experience are rare so seek them out and then enter into a dialogue with them, enquire about their personal rebreather diving activity outside of training, satisfy yourself that they have a good reputation by speaking with former students. Any rebreather instructor who takes seriously the business of quality instruction and training safety should not be offended by such enquiries. Indeed, from the instructors perspective it suggests a potential student who takes their diving seriously and should be welcomed. Like everything in life, you get what you pay for, high quality rebreather instructors are specialists so be prepared to pay a little extra for that specialisation, its an investment you will not regret, you will get back so much more in return.

### **Understand Constant Oxygen Partial Pressure**

Always know your PO<sub>2</sub> (oxygen partial pressure). However it is simply not enough to 'always know your PO<sub>2</sub>', of greater importance is that you understand your PO<sub>2</sub> and the potential implications should you embark upon a particular course of action. When you use a rebreather you breathe from an artificial environment and during an emergency, if the electro / mechanical PO<sub>2</sub> management or monitoring systems fail, for a short period at least, you may require to safely manage this artificial breathing environment.

When moving from open to closed circuit SCUBA, you must alter your thought processing from a fixed oxygen percentage to a fixed oxygen partial pressure if incorrect decisions are to be avoided. Understanding a fixed oxygen partial pressure and its potential implications must become intuitive, simply knowing your PO<sub>2</sub> is insufficient. I have witnessed on numerous occasions rebreather divers making an incorrect decision when they knew their PO<sub>2</sub> in numerical terms but failed to understand the reality and implications of the numbers (PO<sub>2</sub>) being displayed. For example, during a rebreather instructor training course, an oxygen addition valve (solenoid) failure occurred and the PO<sub>2</sub> was allowed to drop to a level that eventually triggered a dangerously low PO<sub>2</sub> alarm. The initial emergency response was correct, an immediate and effective diluent flush elevating PO<sub>2</sub> to a temporary safe level. However the subsequent action was to spend too long trying to diagnose the problem and then to ascend directly to the surface breathing from the 'loop'. At this point the instructor candidate was prompted to go to open circuit before the ascent was made. When questioned post-dive, the diver thought that it would be safe to ascend on the 'loop' as we were only in 15m of water and at a safe ascent rate it would only take a minute to reach the surface/safety. Had he done so he would have likely lost consciousness before he made it to the surface as his PO<sub>2</sub> was down to 0.25 bar before the intended ascent was due to commence. This demonstrated a fundamental lack of understanding of the effects of a fixed / constant PO<sub>2</sub>.

### **Use Pre / Post Dive Checklists**

Use a pre / post dive checklist: it consistently takes you through the necessary stages without you having to rely on memory. It also allows you to walk away from your pre / post dive process or be distracted and return to precisely where you left off, again without relying on memory. If structured accordingly and retained for future reference, a pre / post dive checklist automatically serves as a maintenance management system providing a means to log routine servicing, oxygen / battery replacement dates, cylinder inspection dates and any unusual technical events. This provides a documented means of following a fault trend to help you pre-empt a critical failure, for example an oxygen sensor with a lower output or slower responding than the others.

Outside of military diver training, the rebreather I frequently instruct is the APD Inspiration, not because I have a preference for this particular rebreather, it simply presents the greatest demand for training at present. The pre / post dive checklists I insist my students use during my instruction may be downloaded from [www.haynesmarine.com](http://www.haynesmarine.com) and can be adapted / modified to suit any particular rebreather. In addition, a Megalodon CCR (CE Version) pre / post dive checklist is also available.

### **Continued Personal Development**

Behavioural researchers have determined that it generally takes twenty repetitious days to turn a skill into habit, you absorb only 25% of what you are taught, an additional 25% of the information provided is assimilated through later reading and review during the instructional period and the remaining 50% of what you are taught must be rediscovered through your own experience. Place this into the context of a typical five-day rebreather course and you can begin to appreciate the limitations of such a course and the end product, i.e. the newly certified rebreather diver.

Rebreather training curriculums provide the knowledge and skills needed to get you safely into, and more importantly out of the water when faced with a variety of emergency scenarios. However by the end of a five-day rebreather training course, that typically incorporates eight to ten hours of dive time, no skill has yet had time to become a habit and only 50% of the instruction has been assimilated. This leaves a large competency gap that must be bridged by the newly certified rebreather diver post training. To limit exposure to potential harm, this must be undertaken in controlled stages and may be considered an apprenticeship.

When everything is going well, rebreathers are easy to use, deceptively easy, not so however when they fail. Post-training over confidence is typical often leading to diving beyond current ability. Therefore grow your experience gradually and continue to practice emergency response skills. However, regardless of your rebreather experience, personal development is important to all rebreather divers, new and old, so continually study and in particular learn from others mistakes. Unfortunately many an experienced open circuit diver during the early stages of rebreather diving have confused confidence with current ability and as a result never survived long enough to serve out their rebreather apprenticeship. Don't fall into the over confidence trap.

My rebreather diving mistakes over the years are numerous and if we are honest, those of us with a long history of rebreather diving are here today, to a greater or lesser degree, as a result of good luck. Luck may be likened to loose change in your pocket. You wander down the high street on a Saturday afternoon, pop into a few shops and before you realise, your change has run out. For some, this unfortunately happens sooner rather than later.

Before your pockets are empty of luck, you need to continually top up your intellectual and rebreather skill 'bank accounts' with knowledge and practice so that when 'hard times' come, as they inevitably will, you've got sufficient savings to increase the likelihood of making it through. Place too much reliance on a pocket of dwindling 'lucky coins' and the likelihood of making it onto the infamous rebreather fatality list increases. Therefore

continue to study long after formal rebreather instruction has ceased and take every opportunity to practice emergency procedures.

### **I've Always Done It This Way, Why Change Now**

Having always done something in a particular way does not necessarily mean it to be correct or mean that it will not eventually result in an adverse outcome. If I was to summarise the single most important thing I have come to learn over two-decades of rebreather diving, it is that the more I learn, the more I have come to realise how little I know. If you are already a rebreather diver, continually challenge your behaviour, habits and your perception of what you consider correct or appropriate. Maintain an open mind, there is always room for improvement in every facet of our diving, regardless of who we are and our experience.

### **Rebreather Diving Hours Do Not Necessarily Reflect Experience**

Whilst extensive use in a variety of environments is a key element to gaining rebreather competency, I witness or review reports of experienced technical and military rebreather divers, who at potentially life critical junctions make incorrect choices. Whilst there is no doubting that many of these divers have plenty of rebreather in-water time, life support equipment fails infrequently, so when it does, divers are often not prepared and consequently make fundamentally incorrect decisions. Survival often then came down to how many 'lucky coins' are still in the diver's pocket. Your rebreather survival strategy should not be based on good fortune!

One of the personal motivations to instruct rebreather divers and coach rebreather instructors is that it helps maintain my failure response skills and ensures that the "what will I do if" is at the forefront of my mind being continually questioned, reinforced and rehearsed. For many rebreather divers, the "what will I do if" thought process and skills appear to have been left behind many years ago, possibly soon after they completed their initial rebreather training. This explains at least in part why many experienced rebreather divers make incorrect decisions at life critical junctions; yes they are experienced, but they are experienced in things going right and not necessarily experienced at things going wrong or experienced in pre-empting and rehearsing things going wrong.

Avoid falling into the trap of experience self delusion, instead strive to become a 'rounded' rebreather diver practiced in the anticipation and mental and physical rehearsal of failure modes and associated emergency response. Where the environment is appropriate, this can be accomplished by making a point of rehearsing an emergency skill on each dive; remember though to pre-warn your dive buddy / dive team of any planned skills practice and at what point in the dive.

## **PART 3: BE PREPARED**

### **Self Discipline**

Each time I prepare my rebreather I pause and say to myself, "if allowed to, this could kill me today, I must prevent it happening". It's a simple ritual that goes unnoticed by those observing, however it focuses the mind on the task in hand and away from distractions.

You have to be disciplined to safely use a rebreather over an extended period. Consistently pay the same level of attention each time you fill your canister, calibrate the oxygen sensors and pre-dive test the rebreather. Part of this discipline is time management, you are unlikely to correctly prepare your rebreather if under time pressure so ensure you allocate an appropriate amount of time for this task. Allow at least an hour, this will generally provide sufficient time to correctly prepare and deal with any minor maintenance issues that might arise.

### **Choose Your Buddy Carefully**

As a buddy dive pair, despite a self-sufficiency state of mind, you are a team. The actions of one team member therefore effects the other. If your buddy ends up in a life threatening position it increases risk to yourself, double fatalities are not uncommon as one tries to rescue another. All of us have days when personal performance is not as good as we would like it to be. However, such days should be infrequent so avoid partnering with persons where poor performance is the norm: those who's equipment is poorly maintained, who experience an above average level of minor incidents, who are disorganised, those you consider to be an incident waiting to happen. Their problem, likely brought upon by themselves, can all too quickly become your problem so think carefully of who you team with.

### **Think of All That Could Go Wrong and Plan Accordingly**

Following an unsuccessful attempt to revive a friend after his body was recovered from a cave, an extract from my dive log entry from that day reads: "*as a reminder to myself in the future, it does not matter how many diving hours I have, I cannot breathe water, think of all that could go wrong*". With over twenty-years of rebreather diving now behind me, that somber dive log entry continues to be the mantra under which my life support equipment is prepared and dive planning conducted, making it yours will greatly enhance your rebreather survival strategy.

### **Eventually Your Rebreather Will Fail**

Prevention is better than cure, however despite all your best efforts to avoid equipment failure, at some point your rebreather will fail to function correctly, so plan on it; visualise failure modes and your response, continually question yourself "what will I do if". However, simply having a mental response to each failure scenario is only part of the answer, be realistic, is your response workable under extreme stress, in low light / visibility and or at depth? If so when did you last rehearse your response to each failure. Don't dive in denial, a significant failure will eventually occur, it's just a matter of time.

### **If Something Feels Wrong, It Is Wrong**

One of the critical differences between Open Circuit (OC) diving and Closed Circuit (CC) diving is that with OC, the major issue is whether there is sufficient gas to breathe, whereas with CC, the major issue is whether the gas you are breathing can sustain consciousness. A rebreather failure, if not quickly addressed, will likely result in a disabling injury. To the unwary, a disabling injury can rapidly effect levels of cognitive function and consciousness, drowning most likely being the subsequent cause of death if self-rescue or buddy assistance is not instigated. Do you know the symptoms of hypoxia, hypercapnia and hyperoxia? If not re-learn them and maintain an active watch for them during each dive.

However, know these symptoms or not, if something feels wrong, it is wrong, that is the reason you are feeling the way you do. Don't second guess or question yourself, act decisively before your judgement is impaired and incorrect decisions made. For those with a mouthpiece integrated bailout valve go directly to open circuit then assess the situation. However, assuming the diluent has an appropriate oxygen percentage for the depth, those who have to remove the mouthpiece to breathe from a separate demand valve, immediately conduct an effective diluent flush to provide a safe PO<sub>2</sub> before closing and removing the mouthpiece, then transfer to a safe source of breathing gas, otherwise loss of consciousness may occur between gas sources.

It is worth noting here that due to the insidious nature of many breathing gas diving maladies, those who solo dive using rebreathers face elevated risk as the ability to self rescue can be impaired before the reality of the situation is fully comprehended. For those without a buddy to provide assistance, the subsequent outcome is predictable and is the likely reason solo diving features relatively highly in rebreather fatality analysis. Following a systematic assessment of risk, there are times when temporarily being separated from a buddy in a controlled and deliberately planned manner may be

justifiable: confined space cave exploration or extended wreck penetration being two such possible examples. Therefore for those who undertake such diving, heighten your awareness of inappropriate breathing medium cause and effect and ensure you have sufficient alternative sources of safe breathing gas readily available throughout the extraction route. However such extreme examples of diving are not the norm, therefore it is recommended you always dive with and remain close to a reliable buddy when rebreather diving. Remember, whilst you may be unable to comprehend your symptoms of an inappropriate breathing gas, an attentive buddy may witness the signs you display. As a result many rebreather divers are alive today for one reason and one reason only: rescue by their buddy.

#### **PART 4: THIS REALLY CAN KILL ME, WHAT CAN I DO TO HELP PREVENT IT**

##### **Gas Analysis**

The use of an inappropriate gas continues to be a cause of diving incidents, some of which are unfortunately fatal and could have been avoided if the gas was analysed correctly and cylinder marked accordingly. Analyse every breathing gas cylinder every time you prepare your equipment, make no assumptions, confirm the oxygen is 100%, confirm your diluent is what you expect it to be, confirm your open circuit bailout and decompression gases are what you expect them to be and that it is apparent to everyone else you dive with what the maximum operating depth and content is. If you dive with gases other than air then you should personally own an oxygen analyser: don't trust other persons gas analysis equipment to be functioning correctly.

##### **Pre-Breathe**

A thorough pre-breathe is a fundamental procedure needed to confirm your rebreather is functioning correctly prior to entering the water. Despite the mandatory need for a 3 to 5 minute pre-breathe, rebreather fatal accident analysis frequently highlights the lack of a thorough, or on occasion a total absence of a pre-breathe. A second dive of the day, particularly if un-planned such as for example re-entering the water to recover lost equipment, is common to rebreather fatalities where something as fundamental as failing to turn on the electronics or open the oxygen cylinder valve results in loss of life. Regardless of the circumstances, always conduct a thorough pre-breathe before entering the water and above all else confirm a safe and stable PO<sub>2</sub>.

##### **Suspected or Known Fault**

I repeatedly witness rebreather divers entering the water knowing there is a potentially hazardous fault with their rebreather. Inevitably the problem frequently gets worse and on occasion becomes a trigger for a subsequent incident. You can never justify diving if the breathing loop fails to pass positive / negative tests or if there is something wrong with the oxygen delivery / partial pressure control and monitoring systems. Would you rock climb with a damaged safety rope or exit an aircraft knowing your parachute was not packed correctly? Of course not, yet when it comes to diving, the drive to get into the water often over-rides common sense. Don't get in the water if you know there to be a fault with your life support equipment.

##### **Cardiovascular Fitness**

Outside of the military, very few of us require high levels of athletic fitness to conduct our dives. However when exercising underwater, in particular when using rebreathers, divers are exposed to significant respiratory loads not encountered at the surface, the key ones of which are:

Resistive effort: breathing resistance imposed by gas flow friction, turbulence and restrictions.

Static lung load (hydrostatic imbalance): resulting from the pressure (depth) difference between the diver's lung centroid and the counterlung.

Therefore help the efficiency of your respiratory and cardiovascular systems by maintaining a basic level of cardiovascular fitness so that in event of encountering a high work rate scenario, physical and psychological stress is minimised.

### **Ventilation**

Having personally experienced a broad range of diving maladies, the one that caused the greatest amount of physical and psychological distress whilst sub-surface was CO<sub>2</sub> poisoning (hypercapnia), which due to the manner in which it is most likely to manifest itself, is the diving malady I have grown to fear most.

Poor canister filling and exhausted CO<sub>2</sub> absorbent are most frequently cited as the cause of hypercapnia. However I believe this not to be the case having had the good fortune over the years to have discussed the subject with a number of leading diving research physiologists.

Assuming the rebreather has been correctly prepared using an appropriate CO<sub>2</sub> absorbent and used within the manufacturer's recommendations, the consensus view is that the most likely cause of hypercapnia when using a rebreather is your own inability to remove CO<sub>2</sub> from your circulatory system and not a failure to scrub it from your exhaled gas. Consider the respiratory loads previously discussed, now consider the fact that human trials have demonstrated that when breathing air, the ability to pass gas in and out of the lungs, in other words the ability to ventilate, is reduced by 50% by the time the diver is at 30m (100ft) and down to 33% at a depth of 45m (148ft). These trials were conducted in a dry chamber with trial subjects wearing 'daily' clothing. This reduction in ventilation is therefore likely to be greater when you consider the restrictive nature of diving suits, harnesses, the burden of a the rebreather upon the person and any elastance inherent within the counter-lung.

What is it that causes such a marked reduction in your ability to breathe? Gas density. Gas density has a profound effect upon ventilation and the ability to remove CO<sub>2</sub> from the circulatory system resulting in a certain amount of 'retained' CO<sub>2</sub>. During increased work-rates this problem is compounded and an ever increasing amount of CO<sub>2</sub> is retained within the circulatory system. In other words, despite a perfectly functional scrubber canister, the diver self poisons as a result of inefficient ventilation.

The UK Royal Navy switches to a heliox diluent for diving beyond 30m for this reason and is the principle reason that a maximum depth of 40m is recommended by most training agencies when using an air diluent. Humans have evolved to breathe air at normobaric pressures. What then can you do to manage increasing gas density with depth and resulting retained CO<sub>2</sub>? If using an air diluent stay shallow and avoid high work-rates. Alternatively, even if you have no desire to extend your diving depth beyond recreational limits, if you wish to limit the likelihood of becoming hypercapnic, take a training course that enables you to safely use a normoxic trimix diluent, the use of which will reduce gas density and thus promote your ability to ventilate (breathe) at depth. Wherever possible, due to my concerns over CO<sub>2</sub> retention, I use a trimix diluent regardless of depth.

### **Oxygen Sensor Moisture**

Water condensate on the face of galvanic oxygen sensors is your enemy. It can impede the passage of gas into the sensor distorting the sensor's output and the PO<sub>2</sub> assumed by the oxygen partial pressure control system, be that system electronic or you manually driving the unit. Worst case, if all oxygen sensor outputs are incorrect, it can potentially result in no or insufficient oxygen being added to the breathing loop whilst a 'safe' PO<sub>2</sub> may be displayed to the diver. Therefore, whenever the environment is suitable, during any surface interval period, allow the area of your rebreather that houses the oxygen sensors to dry naturally. However do not manually dry off the face of oxygen sensors, if the sensor membrane is damaged as a result and the potassium hydroxide electrolyte leaks, the sensor will 'dry out' and early life failure will occur. Worst still, if un-noticed, the



corrosive effects of potassium hydroxide on sensor circuitry and cabling can have a detrimental effect upon oxygen sensor output signals and resulting partial pressure control / monitoring.

### **Mouthpiece Head-Strap**

Looking at rebreather incident reports and in particular the excellent rebreather fatality analysis undertaken by Diver's Alert Network (DAN), although the triggering events and the problem that disables the diver are perhaps most important in understanding accidents and how to prevent them, the fact remains that in most cases the eventual cause of death was drowning. In at least some accidents a disabling problem (such as an oxygen toxic seizure) might not have led to drowning if the diver had been wearing a mouthpiece head strap.

Unless used with a full face mask, every military rebreather I can recall, both of classic and contemporary design, uses a mouthpiece retaining head-strap. The reason for this is simple, in the event of Loss Of Consciousness (LOC) there is a reduced likelihood of dropping the mouthpiece and of subsequently drowning. In other words a simple strap, similar to a mask-strap, secured to the mouthpiece, when worn correctly increases the chances of surviving the most common cause of rebreather deaths. Yet it appears that its use is resisted by both sport rebreather manufacturers and the majority of non-military rebreather divers I have discussed the matter with.

Having a military rebreather diving background, I have been conditioned to use a rebreather mouthpiece retaining head-strap from day one of my rebreather diving career. I continue to do so and I encourage my students and diving buddies to do so. Besides its obvious potential benefit should you fall unconscious, a mouthpiece retaining head-strap relieves the physical effort and resulting jaw fatigue of having to hold the mouthpiece for extended periods. In contrast to common misconception, when removed, pulled down and placed on the upper chest, the use of a mouthpiece retaining head-strap does not prevent or hinder the quick removal of the mouthpiece should you need to switch to an open circuit bailout demand valve.

Thirty years ago in the UK, there was considerable resistance from the motor industry and the motoring public to a proposed new law to make the use of car seat belts mandatory. Thankfully, despite this resistance the law came into force and driving accident fatalities immediately dropped by a significant amount. Today very few of us would consider setting off in a vehicle as either a driver or passenger without wearing a seatbelt, the use of which has become part of driving safety culture.

In my opinion it is likely that the rebreather fatality list would not be so long had the use of a mouthpiece retaining strap been common practice. Again I say be a thinking rebreather diver, use a mouthpiece retaining strap and the probability of encountering the hazard of drowning, the single largest cause of rebreather fatalities, will be reduced.

### **Open Circuit Bailout Gas Calculation**

How much open circuit gas should you carry? There is no absolute answer here, however far too many rebreather divers carry insufficient open circuit bailout gas. I am continually surprised at what experienced rebreather divers and some rebreather manufacturer representatives consider to be an appropriate amount of open circuit gas.

Often it is all too convenient to ignore the reality of the environment you are diving in. For example, if you're at 70m (230ft) and have to swim 50m (160ft) horizontally along a shipwreck at an elevated breathing rate towards the ascent / shot-line, has your bailout gas calculation accounted for this? Yes worst case scenarios are very rare, however the more you dive the greater the probability of encountering a worst case scenario.

Don't follow the masses, be a thinking rebreather diver, calculate your bottom gas bailout gas requirements using a minimum of 50 litres per minute RMV (Respiratory Minute

Volume) with a sufficient allowance for the time needed to return to the ascent / shot-line and an ascent at a safe rate. I recently conducted a 'realtime' bailout on open circuit and based upon gas consumption calculations, my average RMV was 54 litres per minute. In an emergency open circuit bailout scenario, nobody has died as a result of carrying too much gas, whilst some have as a result of carrying too little. An RMV of 70 litres per minute or greater may be achieved during high physical exertion and or a hypercapnic event, therefore keep the 20 litres per minute RMV calculations for decompression gas requirements only.

### **Buoyancy Redundancy**

Looking at the DAN rebreather fatality analysis reports, insufficient gas appears as a common trigger leading to a disabling injury. This may come as a surprise to many, rebreathers have after all a long duration potential. However the pressure vessels used to store gas (cylindrical or spherical) are of low volume, typically 2 to 3 litres. Any loss of gas system integrity can quickly reduce the actual amount of gas available for routine or emergency use.

With this in mind, diluent gas should be used solely to provide breathing loop volume and buoyancy control device (wing) inflation. Beyond these functions, the diluent supply should not be used for drysuit inflation and or open circuit bailout. If you use a drysuit, use an independent drysuit inflation cylinder and draw your open circuit bailout from an independent source of sufficient volume / pressure for the intended dive. A 3 litre diluent cylinder is quickly depleted at high work rates typical of an emergency scenario. If all your source of buoyancy gas is also drawn from the diluent cylinder, the means of providing positive buoyancy, particularly if the breathing loop is flooded, is seriously compromised as the diluent supply becomes ever depleted.

### **Canister Duration**

The maximum duration of a canister is dictated by the manufacturer's test data and the resulting recommended conditions of use. These recommendations should be based upon empirical un-manned testing under strictly controlled conditions that include water temperature, depth (pressure), breathing rate, tidal volume, gas moisture content and Carbon Dioxide (CO<sub>2</sub>) injection rate.

Canister performance is a critical element of your life support system, don't purchase a rebreather unless the manufacturer presents credible independent canister performance test data against internationally accepted standards.

For diving safety, canister test parameters, such as for example those dictated by the European standard EN14143:2003, tend to simulate conditions that may not be typical of the majority of dives (cold water and a constant high diver work-rate simulation). Believing diving is to be undertaken in less challenging conditions than those stated by manufacturers recommendations or under which the canister was un-manned tested, warmer water for example, exceeding manufacturer canister recommendations is not uncommon amongst the rebreather diving community, particularly during exploration diving that requires extended in-water time.

Canister performance is a complex and subtle subject that challenges many a scientist and life support engineer. Current canister performance standards, both military and civilian, are limited in their scope and only determine 'performance' under prescribed steady state conditions. Diving is a hugely dynamic activity and can be significantly removed from the steady state test conditions of a laboratory breathing simulator; note the word simulator because that is all it is, i.e. a machine that tries to simulate human ventilation. Much of the adventurous CCR diving being undertaken is out with the canister 'performance' test conditions as a result of the dynamic combination of inert gases, varying depths and water temperatures, breathing rates / gas velocity through the scrubber bed and CO<sub>2</sub> production. Therefore do not automatically assume that canister test standards are extreme and do not apply to your diving environment or activity.

Whether your rebreather incorporates a temperature based scrubber 'health' indicator and or a CO<sub>2</sub> sensor or not, if you are nearing the end of the canister life where the depth of the effective scrubber bed is reduced, if your work-rate and therefore the gas velocity through the remaining effective scrubber bed increases, CO<sub>2</sub> breakthrough can occur very quickly leading to debilitating levels of inhaled CO<sub>2</sub>. Canister performance standards do not simulate this and therefore do not indicate a canister's CO<sub>2</sub> removal capacity towards the end of a canister's life should breathing rates suddenly increase. Therefore do not continue to breath from the loop at elevated levels if you know you are nearing the end of or have exceeded a canister's recommended maximum life.

There may be rational justification why manufacturer's canister duration recommendations could be exceeded under certain conditions of use, however, unless supported by test data, exceeding maximum duration recommendations places the diver into a large grey area of subjective assessment. This area of uncertainty can be compounded if the canister is stored between dives for extended periods where loss of CO<sub>2</sub> absorbent moisture may have occurred. Therefore, for the vast majority of rebreather divers who have no exploration mission to justify exceeding manufacture recommendations, always remain within the manufacturers stated canister life; for the cost of a canister fill it is simply not worth the gamble to do otherwise.

For those whose mission requires dives that exceed manufacturer's recommended maximum canister duration, think carefully about the conditions of use and what can be done to augment canister performance and reduce work-rate (inert gas selection, canister thermal insulation, the use of diver propulsion vehicles). In addition, canister failure due to unforeseen circumstances such as higher than expected CO<sub>2</sub> production rates, must feature prominently in the project risk management and alternative life support plans.

### **Oxygen Sensor Linearity**

To maintain an accurate PO<sub>2</sub> and provide advisory and alarm information at the correct PO<sub>2</sub> levels, it is essential that oxygen sensors are linear throughout their effective working range. To accurately advise of a hypoxia or hyperoxia hazard, oxygen sensor linearity requires to range from approximately 0.16 bar to 1.80 bar. A worst case failure scenario is when all the rebreathers oxygen sensors are current limited and display a PO<sub>2</sub> that is lower than the actual PO<sub>2</sub> being breathed. Oxygen sensor linearity must therefore be frequently checked.

The ideal and most accurate means of tracking oxygen sensor linearity in the hyperbaric range is to use a suitable pressure test chamber, where depth (pressure) and the gas content within the test chamber can be precisely controlled. However for those who do not have access to such a facility, at the end of each dive, when at 6 metres conduct an effective oxygen flush ensuring that each sensor output displays between 1.5 bar to 1.6 bar PO<sub>2</sub>. Achieving a PO<sub>2</sub> of 1.6 bar at exactly 6m is not always possible due to inert gas / humidity 'breathing loop' dilution, however this will provide a reasonable assessment of oxygen sensor function in the hyperbaric range and a certain level of confidence that the oxygen sensors are 'healthy'. If a sensor fails the 6m oxygen flush test it should be discarded.

Consider also that there is a strong case to be made for staggering the exchange of oxygen sensors to avoid the potential of a 'batch failure' of all sensors. Should it occur during a dive, PO<sub>2</sub> management will be compromised and may result in a hypoxia, hyperoxia or decompression sickness hazard.

### **Maintenance**

Failure to appropriately maintain a rebreather or incorrect maintenance is another prominent feature of fatality analysis. I frequently hear the phrase "if it isn't broken, don't fix it". Such a 'philosophy' must not be applied to life support equipment. Periodic

preventive maintenance must be undertaken to reduce the likelihood of, or to help identify a critical failure before it occurs. In addition, any preventive or corrective maintenance must be undertaken by a competent person trained in the appropriate maintenance procedures. Home repairs are often inadequate and or inappropriate and have been the trigger for a number rebreather incidents. Be diligent and adopt a systematic periodic preventive maintenance programme. If you're not trained to undertake a specific maintenance task then have the maintenance conducted by someone who does have the appropriate training and experience using manufactures original spares.

### **Modifications**

Rebreather modification again features in fatality analysis. What might appear a simple build-state change can have a significant detrimental effect upon life support system function. The law of unintended consequences can come into play and a modification that might have been intended to enhance safety can unknowingly have the opposite effect. When you alter any life sustaining aspect of your rebreather and change the original manufacturers build-state, related life support test data may be invalidated. PO<sub>2</sub> control, work of breathing and canister performance are fundamental life sustaining features that the manufacturer may have spend a considerable sum of money on un-manned testing to determine a particular rebreather's performance and limitations. Don't alter any of these features unless the changes have undergone empirical testing to confirm there is no detrimental change to performance.

## **PART 5: ITS FAILED, WHAT NOW**

### **Prioritising Emergency Response Actions**

In parallel with the sport / technical diving world, the use of electronically controlled rebreathers within military diving is on the increase. As well as civilian technical diving instruction, I travel the world training Naval Explosive Ordinance Disposal teams, Special Operations Forces and Law Enforcement Agencies in the complete range of rebreather technologies.

Regardless of the nation or operational team I am training, I consistently hear diving supervisors brief their divers: "in the event of emergency, inform your buddy and or the surface of the problem then conduct the appropriate emergency procedure". Whilst this may not be incorrect, I believe the prioritisation of actions not to be the most efficient means of addressing a potentially life threatening scenario.

For example, I can recall at least two incidents in the last decade where a diver when faced with an electronics system shut-down or flashing red LED Head Up Display (HUD) warning of a potentially life critical malfunction, first attracted the attention of his buddy and showed him the alarm state before taking any further action. This suggests a psychological reliance on others to help manage the emergency and possibly stems from historical training methodology that emphasises 'buddy assistance' as opposed to the more contemporary technical diving approach of self reliance, with buddy assistance as a secondary level of support.

The unfortunate result of what I consider to be incorrect emergency procedure prioritisation was one fatality and a one near miss. Despite this, the emphasise to let others first know there is a problem remains 'carved in stone' and has been reinforced with the increasing use of through water communications. In contrast I recall reading that following a review of human stress response during a life critical emergencies, the National Aeronautics and Space Administration (NASA) trains it pilots to respond by prioritising their actions as follows: aviate, navigate, communicate. In other words first get control of the aircraft and orientate yourself, take the aircraft to a safe place in the sky on a heading that takes you away from danger, then let people know what the problem is and how they may be able to assist. There is a strong emphasise on self reliance within this prioritisation; you are the best and often only person who can deal with the

emergency so waste no part of your mental and physical effort on actions that will not immediately have a potentially positive effect.

During a life critical junction, trying to communicate your situation to persons unable to lend direct and immediate assistance may be futile. Any unnecessary delay in conducting self preserving actions can have fatal consequences; before others have understood you and realised the reality and seriousness of the situation, it may be too late. In an emergency, focus your whole effort therefore on immediate actions you can personally undertake to self preserve. If you survive the initial threat to life and the situation is stabilised, you can then request additional assistance if required. Transposing this approach to diving, in an emergency, once you are breathing from a safe source of gas conduct the following:

1. Get control of your buoyancy (aviate)
2. Orientate and place yourself in a safe place in the water column, which is often as shallow as is safely possible (navigate)
3. When the situation is under control, inform others who may be able to assist (communicate).

Of course this prioritisation may not be applicable to every diving emergency, entrapment for example where a buddy may be required to intervene during the early stage, however the focus of this paper is on life support equipment failure and so I believe the NASA approach to prioritising actions under life critical stress to be relevant to rebreather diver training and diving emergencies in general.

In summary, adopt a self reliance state of mind, if your rebreather malfunctions only you can deal with it so do so immediately, act decisively and without delay, then get out of depth as efficiently as is safely possible.

### **Controlled Ascent At The Earliest Opportunity**

In an emergency, once you are breathing from a safe gas source, move efficiently out of depth to as shallow a ceiling as is safely possible. If you have an in-water decompression obligation, halve your depth at a controlled ascent rate. We are discussing here a life critical emergency so ignore deep stops if you have an in-water decompression obligation or safety stops in a no decompression scenario: decompression illness can be treated, ceasing to exist cannot. Once at half your depth, a decision to further ascend and to what depth can then be made. The psychological and physiological benefits of being out of depth are considerable: increased ambient light, reduced narcosis, reduced gas density, reduced retained CO<sub>2</sub> and risk of associated diver maladies, reduced resistive effort, reduced open circuit gas consumption etc. Only there and when the situation is stabilised consider secondary actions such as for example switching dive computer settings, adjusting decompression schedules, trying to explain in detail the problem to a buddy, deploying a Delayed Surface Marker Buoy (DSMB), analysing the failure etc.

## **PART 6: CONCLUSION**

### **Think Not of Yourself But of Others**

In my introduction I wrote that your demise is the penultimate price of rebreather misuse. I say penultimate because the ultimate price in my opinion is paid by your remaining family and friends and not you, whose existence, and therefore self awareness of having paid a price has ceased. Think therefore not of yourself next time you prepare your rebreather and plan and conduct your dive, instead think of those who will be left behind if you fail to act at every stage to the best of your ability and knowledge.

Imagine now a scenario where you don't return from a dive. Take a minute and consider the pain of those you love and care for. Remain with that thought: parents, spouse, children, siblings, friends, all mourning your death, awful isn't it. The urge for adventure

and challenge, to explore, to seek out, to go where no other person has been before is inherent within most of us to a lesser or greater degree and drives us forward. In the larger picture this characteristic is key to human progress. I would therefore not wish to be accused of 'clipping wings', quite the opposite, be all that you can be and make the very most of what the 'genetics lottery' and your life circumstances have given you. That said, most of us have responsibilities to others, therefore the potentially hazardous situations we place ourselves in should be managed appropriately and risk (a function of hazard and the probability of that hazard occurring) controlled to an acceptable level. I say acceptable, we cannot breathe water so diving can never be risk free, however strive to continually improve upon the management of risk.

There is no doubt that when used correctly and within their design performance and limitations, rebreathers can enhance diving safety. For example, an extended duration provides potentially hours of safe breathing gas thus increasing the chances of survival in an entrapment situation or if lost in an overhead environment; a constant oxygen partial pressure can provide the optimum oxygen percentage with changing depth, a characteristic which if used conservatively can reduce the likelihood of oxygen toxicity and decompression sickness. However rebreather life support technology is complex incorporating many subtleties and whilst it is relatively easy to design and build a rebreather that functions, it is something quite different to design and build a rebreather that performs under the extreme conditions potentially encountered whilst diving, therefore choose your life support system carefully. When you have, source the best training available, gradually build up your rebreather experience in controlled stages, continue to actively increase your knowledge and skills and never stop challenging what you or 'accepted wisdom' consider to be correct.

Diving is an exceptional activity, one of the few remaining pursuits that can take you into the unknown and offer the potential for true discovery. Regardless of the level at which you dive, it expands the physical world in which you live offering an insight to a wondrous environment that for the non diving population can only be seen on the television screen or in a book. With so many facets to the activity of diving: physiology, physics, chemistry, engineering, oceanology, meteorology to name but a few, should you wish it to, diving is one of those rare sports that continually broadens your understanding of the environmental forces that shape our planet and the life upon it. As a result, for many of us diving has come to mould our lives and personal development, ultimately in many cases defining who we are. This journey however is not without its down side, the spectre of serious injury or death is always an unwelcome companion on each and every dive. Surviving rebreather diving is a state of mind, therefore, although our ability to restrict the number of rebreather diving hazards and the effect of each hazard is limited, through our actions: preparation, planning and conduct, we can significantly reduce the probability of encountering a rebreather diving hazard and therefore control risk.

***“When you dive you enter an alien world, death is evolution’s default state; your life support equipment will at some point fail, plan on it”.***

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Paul Haynes  
Director, Haynes Marine Ltd.  
CCR Mixed Gas Instructor Trainer

**Caution:**

A Survival Guide To Rebreather Diving has been written to assist with the promotion of safe rebreather use amongst the sport and explorer diving community. However the implementation of all or part of this guidance is at your own risk and the author accepts no responsibility or liability.

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