

REBREATHERS AND CO₂

– FACT, FICTION AND VOODOO

FACT

Closed-circuit rebreathers (CCRs) are popular in advanced recreational and military diving owing to advantages such as minimization of gas consumption, the optimizing (reduction) of decompression and the ability to provide a low signature. Rebreathers recycle expired gas around a closed loop circuit using one-way valves. Expired carbon dioxide (CO₂) is removed as it passes through a 'scrubber' canister containing CO₂ absorbent.

The most commonly used absorbent is soda lime (a mixture of sodium hydroxide and calcium hydroxide).

Rebreathers are more complex than open-circuit scuba equipment and can be prone to operator errors. Some of these relate to the CO₂ scrubber and its use. The absorbent material has a finite capacity and must be changed regularly.

Errors include failing to replace the absorbent material when required, incorrect packing of the absorbent canister, incorrect installation of the canister in the rebreather and, rarely, forgetting to install it (or the material) entirely. Such errors may allow expired CO₂ to enter the inhaled gas which may in turn cause symptomatic CO₂ toxicity (hypercapnia).

Hypercapnia is also known to speed the onset of oxygen toxicity and the narcotic effect of nitrogen breathed at higher partial pressures.

How do we deal with increases in CO₂?

Put simply, as a mechanism, with increased workload the body generates more CO₂. For analysis purposes this is recognized as arterial CO₂. Arterial CO₂ is detected by the brain. Arterial CO₂ will rise as CO₂ production rises or ventilation (breathing) falls.

The brain's mechanism to deal with CO₂ can be summarized as a two-fold approach:

1. Increase ventilation to maintain CO₂ at nominal limits.
2. Conserve energy and let CO₂ rise.

Our ability to ventilate correctly is a function of depth (gas density) and the breathing resistance within the breathing loop.

To illustrate the effects of this, in a study¹ tests subjects were exposed to varying levels of inspired CO₂ with and without breathing resistance. Three results were summarized as:

- Elevated CO₂ with breathing resistance added, produced an increased ventilation that moderated (but did not stop) CO₂ increase.
- No CO₂ but elevated resistance added produced no rise in ventilation rate and CO₂ retention occurred as in a working (functioning scrubber) rebreather with excessive breathing resistance.
- Moderate depths (18 meters) was shown to reduce the effectiveness of ventilation in removing CO₂ due to gas density, lung stiffness etc. and therefore the ability to control CO₂ through increased ventilation is reduced with depth.

In summary, in considering the effectiveness of CO₂ removal, a secondary factor related to the breathing resistance (Work of Breathing/WOB) of the rebreather must be considered and this increases with depth.

The effects of CO₂ retention were further expanded on in a study² referenced in figure 1. The red line records the CO₂ passing through a scrubber canister (the spikes are analyzer calibration runs) and clearly show that the scrubber is functioning correctly (almost no CO₂ breakthrough). The blue line references CO₂ measured at the end of each breath (end tidal CO₂) recorded at three work rates (80watts, 125watts and 100watts). The dotted black line is the maximum allowed limit of end tidal CO₂ and the graph clearly shows that while the scrubber is functioning perfectly, the end tidal (retained) CO₂ rises above acceptable limits as workload (as a function of gas density or WOB) increases.

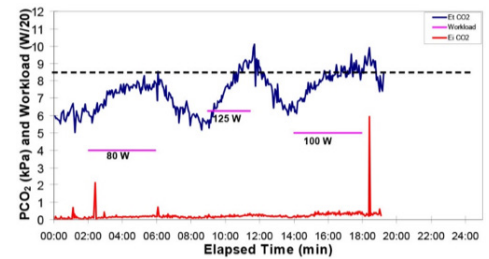


Figure 1
– CO₂ retention as a function of workload

Work of Breathing

Work of breathing (WOB) put simply is the effort required to 'push' gas around the breathing loop.

It is a combination of the resistive (restrictive) elements of the loop (small hoses etc.) and the pressure difference (distance) between the counterlungs and the lung centroid. This distance adds to the resistive element and changes as the diver rotates in the water.

WOB increases with depth and gas density.

As previously discussed, elevated WOB can lead to CO₂ retention.

Linked to this, gas density trials have been conducted where groups of divers were exposed to increased gas density and then their cognitive function was tested.

The following graph³ (figure 2) details a series of tests at elevating gas density in grams/litre (g/l). Looking at the first column where the gas density was 2 to 3 g/l, 439 tests were completed. 393 completed successfully, 31 failed for reasons other than perceived CO₂ issues and 15 failed because of 'recognized' CO₂ issues. Conversely the last column where the gas density was 6 to 7 g/l, only 35 completed successfully and 31 failed due to CO₂, almost 50/50 (ignoring the 'other reasons'). Therefore, the elevated gas density which in turn created an elevated work of breathing generated high failure rates.

The study suggests that ideally gas density should be below 5.2 g/l or air at 31m and definitely not exceed 6.3 g/l or air at 39m.

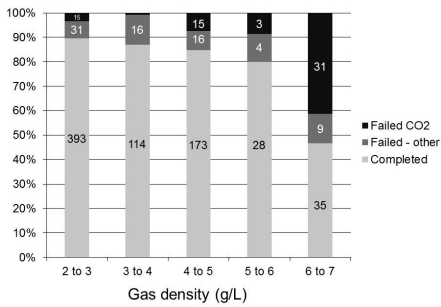


Figure 2

- Test failure due to increased gas density

FICTION

The following items can be considered as common misinformation and should be treated accordingly. In short, all of the below are NOT true.

- All CO₂ absorbent is of similar design and generates similar performance. Therefore, I can put any absorbent in my rebreather and it will perform within the manufactures published limitations. **Author's note:** There is a large selection of CO₂ absorbents used across the medical, diving and other industries. Each has unique properties ranging from shape and construction through to chemical makeup and water content. Only Diving Grade absorbent should be used for diving.
- The published CO₂ endurance times for my rebreather can be conducted at any depth, in any water temperature and at any work rate. Therefore, these three variables do not have any affect on the ability of the scrubber to remove CO₂. **Author's note:** Scrubber endurance can be massively affected by these variables. In addition, each rebreather's specific design can affect the endurance so a duration obtained with an absorbent type in one rebreather will not be the same in another rebreather.
- One type of scrubber design (be it radial, axial, cross flow etc.) will always perform better than another. **Author's note:** Historically it was thought that radial designs always gave better performance, but this is not universally true and in reality, axial designs are often better performers.
- Post dive, rebreather absorbent can be removed, dried and refitted to improve performance. **Author's note:** This is VERY dangerous.
- I can store a part used scrubber indefinitely and use again and obtain the same performance. **Author's note:** The variabilities of container integrity and water content loss (evaporation)

make this a dangerous assumption. While there have been tests using new absorbent at differing storage conditions⁴, this procedure should not be relied on.

- Advanced CO₂ absorbents such as lithium hydroxide can be safely used in an underwater rebreather. **Author's note:** Lithium hydroxide (while very efficient as an absorbent) is an extremely volatile chemical composition and reacts aggressively with water. It should not be used in rebreathers.
- Out of date absorbent, as long as it is in a sealed container, can be used. **Author's note:** Again, this procedure cannot be relied on. Out of date medicines would not be used, so the same applies to absorbent material.
- In a breathing loop the CO₂ scrubber is the most important element for managing CO₂ around the loop. **Author's note:** Obviously the scrubber is vital for removing CO₂ but even a partly used or poorly packed scrubber is not as dangerous as a failed mouthpiece mushroom valve. The first test of any rebreather setup should be for mushroom valve integrity.

VOODOO

Comparing endurance

Divers obviously need to know how long their rebreather will continue to remove CO₂ from the loop in use and manufacturers would ideally want to quote a duration as guidance. This is difficult to quantify because a rebreather scrubber's ability to remove CO₂ is a function of several variables:

- Work rate (metabolism and therefore CO₂ generation).
- Ventilation rate (primarily as a function of work rate).
- Water temperature.
- Absorbent type.
- Rebreather design (primarily as a function of heat loss).
- Depth (primarily as a function of gas density).

This often creates a dilemma, especially for manufacturers. The ideal solution would for all manufacturers to quote an endurance based on a worst case scenario. This would then create a 'level playing field' from a user information/safety standpoint. This is exactly what the CE test standard for rebreathers (EN14143) tries to

do, in that it uses the following parameters as a test requirement;

- 1.6l/min CO₂.
- 40l/min ventilation.
- Water temperature 40°C.
- Depth 40m (an additional test at 100m is used for heliox/trimix rebreathers).
- Diluent air.

The current reality is that test results obtained using these parameters do not make some rebreathers 'look good' from a performance perspective in that they do not live up to their manufacturers initial design expectations, this creates a marketing issue.

Often the end result is that within operating instructions, while testing to EN14143 will be referenced in a manual, there will be a caveat that references a change in the parameters such that the endurance figure is increased.

While the CE parameters are arguably extreme in relation to sport diving they do provide a good safety net and especially for technical/military diving profiles and/or when high work rates are experienced towards the end of a scrubber's life.

The end result is users must beware when comparing rebreather performance and should check with the manufacturer if there appear to be any ambiguities at all in the quoting of endurance figures.

The 5 minute pre-breathe

Historically, a scrubber integrity test conducted by divers is to breathe an assembled unit for 5 minutes in order to generate symptoms of hypercapnia experienced as a result of a failing scrubber or sealing system that in turn may create a bypass of CO₂. This process has several issues such as 'how large' is any bypass and can we physiologically detect that level?

In a trial completed⁵ in New Zealand, the following observations were noted:

The five-minute pre-breathe is an insensitive test for CO₂ scrubber function in a diving rebreather, even when the scrubber canister is absent. A pre-breathe is nevertheless recommended for purposes such as checking the function of the oxygen addition system before entering the water, but a duration less than five minutes should be adequate for that purpose.

Arguably the most important secondary finding of our study is that partial scrubber failure in a rebreather is a particularly insidious fault if divers rely on a pre-breathe to detect it. By modestly increasing ventilation, subjects typically maintain

normocapnia during a surface pre-breathe in this condition, resulting in a false negative that is dangerous because normocapnia is much less likely to be maintained during the dive itself.

The observations from this trial point to the fact that the only reliable test of a scrubber systems integrity should utilize a gaseous CO₂ sensor.

All absorbents are the same

As previously mentioned, there are several manufacturers and types of commercially available absorbent. A common misconception is that 'absorbent is absorbent' and one will last just as long as the other.

Again, in a New Zealand trial⁶, two common diving absorbents were tested.

Author's note: *These tests were completed at surface pressure and testing at depth will change the results although the relationships will remain broadly the same.*

Sofnoline 797⁷ (maximum granule size 2.5mm) and Spherasorb⁸ (maximum granule size 5mm) were tested with the following results.

The mean operating duration to CO₂ breakthrough was 138 +/- 4 (SD) minutes for Spherasorb and 202 +/- 4 minutes for 2.64kg Sofnoline. **Author's note:** *Spherasorb weight not referenced, likely to be less due to lower bulk density of Spherasorb. The difference between the peak respiratory pressures was 10% less during use of Spherasorb, suggesting lower work of breathing.*

Under conditions simulating work at 6MET during use of a rebreather, a canister packed with Spherasorb reached CO₂ breakthrough 32% earlier with 10% less mass than Sofnolime packed to similar volume. Divers cannot alternate between these two preparations and expect the same endurance.

The scrubber 'curve'

When tested at a steady depth, temperature and CO₂ generation rate, the CO₂ 'curve' is mostly a flat line (0mb CO₂) for at least 2/3rd of the endurance time. In the last 1/3rd it starts to rise until it passes the 5mb and then 10mb safety alarm limits⁹. The 'lift' towards 5mb often only occurring in the last 10-15% of the endurance time and the rise to 10mb in the last 10-20 minutes or so. At first glance it would appear that we can safely exercise right up to nearly the end of the scrubber life without a bypass taking place, even at the extreme CE test rate and/or having ill effects due to hypercapnia.

The reality is not so simple and can depend on several elements such as

rebreather design, increased ventilation rate. In addition, the increased ventilation can produce an increase in work of breathing and the associated CO₂ retention, especially at depth.

Unmanned trials do however indicate that in the first 2/3rd of the scrubber life, even with increased ventilation/work-rate that the scrubber can 'cope'. However, it is clear that this is not always the case in the final 1/3rd.

CO₂/endurance sensing

Gaseous CO₂ sensors are not new and have been used in surface applications for years, and are a way of instantly measuring CO₂ in a breathing loop.

More recently a form of CO₂ sensor has been used for diving with rebreathers. It is known as a non-dispersive infra-red (NDIR) sensor. Put simply, using infra-red light it measures the spectral response of CO₂ when the light is passed over it. Unfortunately, the spectral response of water is similar to CO₂ and can also be detected. This can create a 'false positive' (high reading) and a shorter dive endurance, which in itself can be seen as a 'fail safe' scenario. Some manufacturers have successfully integrated NDIR sensors in rebreathers with additional moisture filtration, sometimes at the expense of sensor response time and long duration use (due to filter degradation) is still potentially an issue. Gas density can also affect these sensors but can in most cases be compensated for.



Figure 3 - Experimental CO₂ sensor

Another, less common sensor used uses a chemical gel patch which changes colour as more or less CO₂ passes over it. This change is then measured and directly correlated to a CO₂ level. These are less prone to moisture interference and are gas density independent.

Gaseous sensors aside, a scrubber's endurance prediction is the next challenge. Current systems rely on the fact that as absorbent is used within a scrubber housing, a thermal 'front' slowly moves through the scrubber tracking the active section of the absorbent. As that section is used, the front moves on. This

thermal front movement can be detected using a series of temperature sensors (a thermal array) arranged linearly within the scrubber. As each sensor peaks, then a percentage remaining can be estimated and compared to a tested endurance to predict time remaining.

While thermal array monitors are a good steady state system, accuracy is challenged in shallow and warm water and it cannot predict bypass as a result of high workload.



Figure 4 - Thermal front monitor – AP Diving

In short, all types of sensor have one issue or another that can also relate to how it is deployed within the rebreather. The only way to verify suitability is to review test results.

In summary, gaseous CO₂ sensors help with:

- Bad CO₂ seal
- Bad absorbent
- Absorbent abuse (used too long, repacked)
- Breakthrough due to high work

Gaseous CO₂ sensors do not help with:

- Detecting CO₂ retention
- Duration monitoring

Thermal arrays help with:

- Endurance prediction

Thermal arrays do not help with:

- CO₂ bypass as a result of high workload/seal failure

Choosing an absorbent

The correct choice of a CO₂ absorbent product may not be as simple as it first seems. For a lot of divers, cost is an issue. For others, especially deep divers, it might be endurance or work of breathing.

The key point here is you need to decide what your objectives are and above all you should prioritize safety as the driver.

As an example, if you are only conducting short, shallow dives then a product that is more cost effective at the expense of endurance may be applicable.

If all your diving is in warm water, then again a less efficient product may be suitable.

Conversely, if you diving is deep, long and cold then ideally would want the best performing product possible from an endurance perspective. That should be balanced against any work of breathing issues of a potentially more densely packed (smaller granules) absorbent if that is the choice, much of the latter being mitigated by using the correct diluent at depth.



Figure 5 - Absorbent friability should be considered

Consideration on long dives should also be given to the product's 'friability', its tendency to break into smaller particles, bypass any scrubber filtration and mix with condensed water to generate a caustic cocktail. Friability is tested for by most manufacturers and can normally be simply evaluated by comparing how much dust there is at the bottom of a used barrel of product.

The bottom line with absorbent use is, you have choices, make them wisely.

Safety Top 10

1. Find out and understand the CO₂ endurance limits of your chosen rebreather design.
2. Hypercapnia is insidious and potentially lethal – do not assume you can detect or 'handle' it.
3. Use absorbent that has been qualified for your rebreather and is in date. Be fully conversant with the manufacturer's test data. You have a right to ask, use it.
4. Do not assume all absorbents give the same duration.
5. Understand the scrubber curve, avoid high work rates towards the end.
6. Use the right gas at the right depth to minimize WOB and CO₂ retention. Gas density should not exceed 6.2 g/L.
7. CO₂ sensing is a major safety feature with extended use and changing workload. If at all possible, use a CO₂ sensor.

8. Do not store part used absorbent for later use.
9. Do not rely on the 5-minute pre-breathe as the only CO₂ system test:
 - a. Check mouthpiece mushroom valves on every dive
 - b. Check CO₂ seals
 - c. Properly pack the scrubber
10. Do not dive with a leaking rebreather, this will:
 - a. Increase WOB
 - b. Decrease absorbent efficiency
 - c. May generate a caustic solution that could be swallowed

SUMMARY

The current 'state of the nation' is that there are several types of absorbents available for use. Only a small number of these absorbents have been tested and qualified in the now available larger range of recreational diving rebreathers. As a result, there is some confusion with regard to the safe limits of use.

Military groups do qualify absorbent endurance through testing. However this only provides a worst case (extreme work rate) scenario.

In addition, the complete picture of issues related to CO₂ is a complex event and while elements of it are covered in isolation in most training documentation, the more 'joined up picture' is seldom discussed in detail.

As a user group and as technology evolves, it is vital that we become as educated as possible with regard to the training and management of CO₂. Whether choosing a new rebreather, a training program, a specific manufacturer or an absorbent supplier, it is important that we confirm the detail and validity of the information we receive.

¹Warkander and Shykoff. NEDU dated July/Aug 2012

²Courtesy Gavin Anthony

³Courtesy Gavin Anthony

⁴Diving and Hyperbaric medicine. Volume 48. 2nd June 2018. Pollack, Gant, Harvey, Mesley, Hart, Mitchell.

⁵Diving and Hyperbaric Medicine Volume 45 No. 1 March 2015. Deng, Pollock, Gant, Hannam, Dooley, Mesley and Mitchell.

⁶The duration of two carbon dioxide absorbents in a closed circuit rebreathing system. Harvey, Pollack, Gant, Hart, Mesley and Mitchell

⁷Trademark Molecular Products Ltd

⁸Trademark Intersurgical Ltd

⁹Reference CE EN14143