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The world as it is

Is more complex safer in the case of bail-out rebreathers for extended range cave diving?

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Abstract

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Nowhere is redundancy more indispensable than extended range cave diving. Training and practice in this discipline ensure divers are equipped with backup regulators, gauges, lights, and adequate breathing gas for a safe exit, emergencies, and decompression. Depending on penetration distances and depth, open circuit cave diving may require carrying more gas cylinders than can be logistically managed by the diver themselves while maintaining safe gas supply margins. Consequently, divers are forced to either stage cylinders in the cave prior to the dive or rely on resupply from support divers. Both scenarios have significant drawbacks. Due to the improved efficiency of breathing gas utilisation and other advantages, closed circuit rebreathers (CCR) have enabled extended range cave diving. With increasing depths, penetration distances, and bottom times, these divers must also plan for an increasing amount of open circuit bail-out gas in the event of CCR failure. Staged cylinders have traditionally been utilised, but this strategy has limitations due to the advanced dives needed to place them and equipment degradation due to prolonged water immersion, which can often result in cylinder and regulator corrosion with consequent leakage of contents over time. Consequently, a growing number of CCR divers are foregoing open-circuit bailout altogether by carrying an additional CCR system for bailout. Although these bailout rebreathers may facilitate further exploration and have certain advantages, the risks of diving with two complex machines remain to be clearly defined.

Introduction

"*Redundancy is expensive but indispensable*." – Jane Jacobs

The use of closed-circuit rebreathers (CCR) for scuba diving has increased exponentially in the last decade. It is estimated that as of 2010, there were more than 14,000 active CCR divers worldwide.[1] Once confined only to military operations and to the most dedicated of technical divers, CCRs are now becoming commonplace in the recreational and scientific realms of scuba diving.

The benefits of a closed-circuit system are numerous. CCRs are much more efficient in terms of breathing gas consumption when compared to open-circuit diving, especially during deep water dives. In CCR diving, the only oxygen used is the oxygen metabolised and is therefore not depth-dependent like open-circuit scuba. Inert gases, such as nitrogen or helium, are recycled in the loop and rarely lost, allowing a very large reduction in gas consumption compared to the same dive on open-circuit. In addition, a CCR allows a diver to breathe humidified, warm gas, which becomes increasingly important during long dives when the cold, dry air of open-circuit systems can impair mucociliary transport and irritate upper airways.[2] Furthermore, CCR offers a relatively bubble-less system allowing for a serene diving experience and much more intimate contact with marine life. In the setting of a CCR cave dive, the lack of exhaust bubbles also reduces the likelihood of disturbing fragile ceilings, which could reduce visibility due to falling debris in the water column. Finally, and perhaps most importantly, the CCR allows a diver to maintain a specified partial pressure of inhaled oxygen at any depth to minimise inert gas loading during the descent and bottom phase and optimise inert gas elimination during ascent.

Notwithstanding these advantages, CCRs are not benign nor without drawbacks. It is estimated that CCR use is associated with a four to ten-fold greater risk of death compared to open-circuit scuba diving.[1] The specific etiology of this increased mortality remains unclear although the insidious failure modes in CCR which lead to hypoxia, hyperoxia and hypercapnia are not as easily detectable as failure modes in open-circuit equipment. This leads to a situation where a failure can remain unnoticed until it is too late to arrest the trajectory towards a non-life sustaining condition.

Due to the significant financial, experiential, and educational requirements for CCR certification, it is likely CCR diving attracts an older demographic on average compared to that of traditional open-circuit diving. Along with older age comes an increase in age-related health concerns, such as cardiovascular disease.[3] Accumulating evidence suggests cardiovascular etiologies underlie many scuba diving-related deaths.[4] Superimposed on these age-related health conditions, the complicated nature of CCRs and their requirement for regular and precise maintenance may also increase the risk of diving accidents and deaths.[2] A report for the UK Health and Safety Executive highlighted numerous human factors issues relating to the design, operation and training associated with CCRs, focusing on the complicated nature of the tasks and unforgiving nature of failures compared to open-circuit diving.[5] As a consequence, the report recommended that more be done to expand on the knowledge and practice of human factors in CCR diving operations and training systems.

Of the numerous critical skills mentioned above for safe CCR operation, an efficient bail-out to an open-circuit supply may be the most important of all. Bailing out when diving with a CCR involves at least six steps: closing the mouthpiece of the CCR; removing the CCR mouthpiece from the mouth; retrieving a second-stage open-circuit regulator from another gas cylinder; clearing water from the mouthpiece via exhalation or purging; breathing from the open-circuit or CCR gas supply; and lastly terminating the dive. In an effort to make these six steps a routine and even automatic event, divers rehearse the process multiple times during training and are encouraged to continue rehearsing them even after certification.

Training standards specify that CCR divers should carry enough open-circuit breathing gas to safely allow a diver to terminate the dive, exit the environment, complete any necessary decompression, and exit the water. However, as distances traveled in overhead environments and the times of the decompression extend, the amount of open-circuit bail-out gas may near the financial and logistical limits of possibility. For example, if a cave diver wishes to complete a 2,400 linear metre penetration into the Weeki Wachee/Twin Dees cave system in Florida at a depth of 90 metres of fresh water (mfw), he or she requires 22,650 L of gas, or ten standard 11 L cylinders. This conservative example assumes the diver bails out onto open-circuit gas at maximum penetration, has a respiratory minute volume (RMV) of 14 L·min^{-1}, swims at a rate of 15 m·min^{-1}, and does not perform decompression. Much of this gas will contain substantial amounts of helium and will be expensive. Furthermore, the placement of these bailout cylinders may be increasingly difficult due to depths and penetration distances and may require set-up dives prior to the exploration dive by the diver or other team members that further exposes divers to increased risks associated with equipment failures and physiological stresses/illnesses, especially for deeper sections. Finally, if these cylinders and regulators are left underwater for many weeks or months, as in the case of exploration of Twin Dees cave system in Florida, the cylinders and regulators may corrode and leak the contained gas (Pitkin A, Personal Communication, 2020) (Figure 1).

Figure 1

Two aluminum 11 L cylinders retrieved from the freshwater cave system Weeki Wachee/Twin Dees in Weeki Wachee, Florida after eight months of submersion. These cylinders were staged in this cave system to serve as open-circuit bailout during exploration cave dives requiring thousands of feet of linear penetration at depths exceeding 100 mfw. Note the extensive corrosion at the tank neck and tank valve interface

As a result of these complicated and expensive logistical considerations for traditional open-circuit bailout, the use of dual or bailout rebreathers has started to be adopted. Instead of multiple open-circuit gas cylinders, these divers may utilise two separate rebreathers with separate carbon dioxide scrubbers, counter-lungs and breathing loops. Although the possibility of human error may be increased even further with two rebreathers, the divers are now equipped with two separate breathing systems. No longer is a diver dependent on cylinders cached in the cave system, rather they carry their own bailout throughout the dive. A bailout rebreather utilised in this way should allow for a safe exit in the setting of most issues encountered by the primary unit, such as an exhausted scrubber, failed solenoid/oxygen sensor, or a computer/display problem. On the contrary, a bailout rebreather would likely not be helpful in the setting of a diver experiencing an increased work of breathing secondary to breathing gas density (assuming both the primary and bailout rebreather were utilising the same sources of breathing gases).

History

Cave divers were the pioneers of dual rebreather systems because of the large amounts of open-circuit gas required to reach the surface safely in the event of failure of a primary rebreather during a deep and/or long-distance cave penetration. The first well-documented use of a dual rebreather system was the German cave diver Jochen Hasenmayer's exploration of the Émergence du Ressel in 1981 using his Speleo-Twin Rebreather (STR-80), a dual home-built CCR, which allowed him to dive further into the system than had been possible using open-circuit scuba. Another pioneering underwater cave explorer of the time was Olivier Isler, who employed a dual semi-closed rebreather (the RI2000, designed by him and Alain Ronjat) for exploration in the Doux de Coly in 1989 and subsequently to pass Hasenmayer's limit in the Ressel in 1990. Other European divers have continued to build on their example, such as Reinhard Buchaly and Michael Waldbrenner, who explored beyond Isler in the Doux de Coly in 2002 using twin RB80s, which are semi-closed rebreathers designed by Buchaly.[6] Subsequently, as more rebreathers have become available, dual rebreather configurations are increasingly being utilised by exploration groups all over the world for deep or long-range cave exploration, and occasionally for deep open-water dives. Data regarding real world risk of this approach is not yet available.

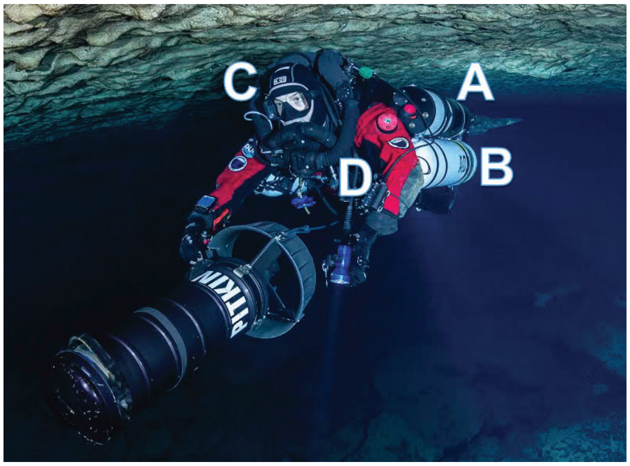
Rebreather bailout configurations

Divers may elect to utilise redundant or dual closed-circuit rebreathers or semi-closed rebreathers (SCR). Although there are advantages to redundant CCRs, they also represent the most additional task loading and maintenance due to their complexity. As such, some divers elect to use a SCR to reduce the complicated nature of the task, while maximising additional safety. SCRs function as 'gas extenders' and continuously add enriched air nitrox (EANx) or trimix (a mixture of helium, nitrogen, and oxygen) to the breathing loop. As the diver breathes and metabolises oxygen, the equipment vents some gas to the water column, while adding additional EANx or trimix to the breathing loop.[7] Although these machines are usually mechanically simpler than CCRs to maintain and easier to operate due to the lack of electronics to measure and/or control the partial pressure of oxygen, they cannot separate oxygen from the vented gas. Thus, they are more wasteful of oxygen and inert gas when compared to CCRs.[8] Of note, as the metabolism of a diver increases, the addition of fresh gas flow must increase to match these metabolic demands. Otherwise, the diver is at risk of hypoxia, unconsciousness, and potentially death.[9] This increase in gas flow is not possible with a SCR mid-dive.

Despite the fresh gas flow cautions of a SCR, the advantages of these units as bailout rebreathers remain. For example, many divers estimate that a SCR is capable of extending the use of open-circuit bail-out by four to ten times. As a result, the diver is usually able to carry sufficient open-circuit bailout gas and a SCR to be capable of individual bailout in the event of primary CCR failure. Divers exploring Twin Dees/Weekie Wachee cave system have recently employed Halcyon RB80 SCRs to facilitate individual bail-out and eliminate the need for the expensive and problematic staging of cylinders in the cave. The Halcyon RB80 is a non-depth-compensated, passive addition SCR (pSCR) in which gas addition is tied to respiratory minute volume (RMV). Its outer dimensions are similar to those of a standard aluminum 80 (AL80 or 11 litre) cylinder. As a result, this unit can be side-mounted, which makes for a more streamlined set-up for a diver with two rebreathers (Figure 2).[10]

Figure 2

A cave diver uses a diver propulsion vehicle and two rebreathers to explore a flooded subterranean cave in southwest Florida. Note the (A) side-mounted SCR , (B) side-mounted open-circuit bailout gas/diluent, (C) breathing loop from back-mounted rebreather, and (D) breathing loop from side-mounted SCR.



Some divers maintain that a fully functional CCR provides the most optimised redundancy while minimising or eliminating the need to carry open-circuit gas. Thus, divers are increasingly incorporating two separate CCRs in their configurations. Some divers utilise both CCRs throughout the dive by regularly switching between the two units, while others utilise one CCR and only periodically check the status of their 'bailout' units. There are certainly disadvantages to these configurations. For instance, a diver now must undertake maintenance of two separate CCRs, which require more work compared to SCRs because of their electronics, computers, and oxygen cells. In addition, a diver must now control and monitor the partial pressure of oxygen and inert gases of not one CCR, but two. Furthermore, unless the team are diving standardised equipment for primary and secondary CCRs (or SCRs), the dive team need to be aware of failure modes and emergency protocols for the team's differing equipment. This increases the initial training burden and continuation training to ensure that competency for emergency drills is both acquired and maintained.

Benefits of a dual CCR approach

While it may seem counterintuitive to suggest that adding a second complicated machine to an already task-loaded diver improves the overall safety profile of a dive, the logistical challenges and dependency on cached open-circuit cylinders may suggest otherwise. For instance, a diver utilising a bailout or redundant rebreather is completely independent in terms of bailout. They no longer depend on carried open-circuit bailout gas or cylinders cached in the cave system which may have corroded and leaked vital gas. This diver is also not reliant on the bailout cylinders of teammates, which is the case when utilising a 'team bailout' approach. Instead, the diver depends solely on his or her two rebreathers as primary and secondary life sustaining equipment. Although an additional rebreather will certainly add to equipment and process complexity, one may interpret this as an overall improvement in safety secondary to a more robust and redundant bail-out procedure as long as a holistic-systems approach is taken to normal and abnormal operations.

In addition to the aforementioned logistical and potential safety benefits, the exploration efforts in Twin Dees/Weeki Wachee in Florida require massive amounts of expensive trimix for the staged bailout cylinders along with support divers/teams to place the cylinders in the cave. These operations are both costly and take time to arrange and to execute. The use of a bailout rebreather allows smaller teams to operate in a more efficient manner.

Risks of a dual CCR approach

Cave diving is an inherently unsafe activity. Therefore, there is always a risk of harm (injury or death) occurring. However, risks can be both negative and positive (opportunities), and the management aspect involves trading one risk against another to achieve a goal influenced by a number of external and internal factors, limitations and constraints. The negative risk of a second rebreather is the potential for an increase in the number and type of error-producing conditions which, if not predicted, detected and corrected, will lead to an increased number of diving injuries or deaths.

The WITH or TWIN model, which was generated by studying human performance in nuclear power operations, considers Workplace design, Individual Capabilities, Task Demands and Human Nature to describe error-producing conditions [Table 1].[11] The WITH/TWIN model considers these error-producing conditions as they are pre-cursors to adverse events rather than outcomes such as 'failure to fill a scrubber', 'failure to properly pack a scrubber', 'failure to fill an oxygen cylinder', and 'failure to turn on an oxygen cylinder'.

These error-producing conditions exist for all levels of diving, but not predicting, detecting and correcting the error when in a underwater cave system and effectively dealing with a failed primary rebreather, individually or as a team, can have fatal consequences.

One specific example from the table above pertains to workload. Research evaluating human productivity in the

Table 1

Examples of error-producing conditions as described by the WITH/TWIN model

Workplace design	Individual capability	Task demands	Human nature
Distractions/ interruptions	New techniques, not used before	Time pressures (in a hurry)	Stress
Changes/departures from routine	Lack of knowledge (faulty mental model)	High workload	Assumptions
Confusing displays or controls	Unfamiliarity with task, first time	Repetitive actions/ monotony	Complacency
Hidden system or equipment responses	Unsafe attitudes	Lack of, or unclear standards	Inaccurate risk perception
Unexpected equipment conditions	Illness, fatigue, general poor health	Simultaneous, multiple actions	Limited short-term memory

setting of multi-tasking, which can occur when a person attempts to perform two tasks simultaneously, switch from one task to another, or perform two or more tasks in quick succession, repeatedly demonstrates an overall decrease in productivity.[12] Even in the case of switching between two predictable simple cognitive tasks, humans are slower to accomplish these processes compared to simple task-repeat; a phenomenon termed "*switch costs*".[13] As tasks become more complex, there are additional switch and time costs.[14] In the setting of CCR diving, especially in the case of dual rebreather configurations, it is certainly reasonable to describe the activity as requiring multitasking. As the research above illustrates, human performance may be impeded with such demands. In the setting of machine failure, bailing-out, and the subsequent stress of this scenario, it is possible that performance would suffer further. Nonetheless, this risk, and others that could be surmised with utilising two rebreathers, must be weighed against the advantages described above to fully grasp the impact of a second rebreather on diving safety.

Conclusions

In the case of extended range cave diving, the trend toward dual or bailout rebreathers may be here to stay. Their use provides significant, and potentially pivotal opportunities for extended range exploration throughout the world. However, the risks and the benefits of such a complex diving configuration should be carefully considered. Divers and explorers need to consider not just the technical aspects of operating the dual CCR as an equipment-based system, but also the socio-technical aspects and error-producing conditions that adding additional complicated equipment has to the wider system, especially when it comes to training for, and executing abnormal operations when workload levels will be high and awareness will be reduced. Nonetheless, as the use of this configuration grows, the risks and benefits will become clearer to investigators and divers alike.

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