Analysis of recreational closed-circuit rebreather deaths 1998–2010

Andrew W Fock

Abstract

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Introduction: Since the introduction of recreational closed-circuit rebreathers (CCRs) in 1998, there have been many recorded deaths. Rebreather deaths have been quoted to be as high as 1 in 100 users.

Methods: Rebreather fatalities between 1998 and 2010 were extracted from the *Deeplife* rebreather mortality database, and inaccuracies were corrected where known. Rebreather absolute numbers were derived from industry discussions and training agency statistics. Relative numbers and brands were extracted from the *Rebreather World* website database and a Dutch rebreather survey. Mortality was compared with data from other databases. A fault-tree analysis of rebreathers was compared to that of open-circuit scuba of various configurations. Finally, a risk analysis was applied to the mortality database.

Results: The 181 recorded recreational rebreather deaths occurred at about 10 times the rate of deaths amongst open-circuit recreational scuba divers. No particular brand or type of rebreather was over-represented. Closed-circuit rebreathers have a 25-fold increased risk of component failure compared to a manifolded twin-cylinder open-circuit system. This risk can be offset by carrying a redundant 'bailout' system. Two-thirds of fatal dives were associated with a high-risk dive or high-risk behaviour. There are multiple points in the human-machine interface (HMI) during the use of rebreathers that can result in errors that may lead to a fatality.

Conclusions: While rebreathers have an intrinsically higher risk of mechanical failure as a result of their complexity, this can be offset by good design incorporating redundancy and by carrying adequate 'bailout' or alternative gas sources for decompression in the event of a failure. Designs that minimize the chances of HMI errors and training that highlights this area may help to minimize fatalities.

Key words

Technical diving, rebreathers/closed circuit, deaths, safety, diving accidents

Introduction

While the principles of closed-circuit rebreathers (CCRs) have been well understood for more than a century,[1] the practical problems of accurate control of the oxygen content of the breathing loop largely precluded their widespread adoption until the development of reliable electro-galvanic oxygen cells in the 1980s. Further developments in miniaturisation and reduction in the cost of these oxygen cells allowed the development of CCRs for the civilian market in the late 1990s.

The development of recreational CCRs was spurred on by the rapid advances in technical diving, which had seen the adoption of mixed-gas deep decompression diving in the civilian sector. The high cost and significant gas logistics associated with such dives on open-circuit (OC) scuba meant that rebreathers offered the potential for divers on limited budgets to engage in dives to locations and depths previously unobtainable. However, it was not long before the civilian use of rebreathers was associated with a number of deaths.[2] Given the small number of CCR units in use when compared to the use of OC scuba, the number of deaths associated with CCRs appeared to be out of proportion, and raised the spectre that there may be some factor intrinsic to the use of CCRs that increased the risk of death.

From 2007, Dr Alex Deas and his company *Deeplife* attempted to document all known civilian rebreather deaths in a database published on the internet.[2] The information appeared to be derived largely from the internet forum *Rebreather World* (RBW).[3] Reports in the 'accident forum' of this site were not independently vetted, but nevertheless were published with both details of the victims and an analysis of the event conducted by *Deeplife*. This database is in the public domain. In early 2008, the Divers Alert Network (DAN) USA in conjunction with Duke University conducted a technical diving conference where a number of prominent members of the diving industry were invited to discuss this database and its consequences. Scrutiny revealed significant inaccuracies in several cases known personally to the participants, including cases known not to involve a CCR. Members of this group agreed to review the database and investigate cases reported to have occurred in their local areas. Obvious errors were removed or corrected and information on the remaining cases was sought and corrected where possible. This 'corrected' database was circulated for internal review only.

The aims of this study were to evaluate the available data and, if possible, to answer several key questions:

- What is the rate of rebreather diver deaths compared to normal recreational scuba diving?
- Is one type of rebreather safer than others?
- Is any one brand of rebreather more likely to be associated with a fatality?
- What are the major causes of rebreather deaths?
- What changes should be made to training on or design of CCRs to minimize future deaths?

Methods

The corrected *Deeplife* database was accessed and the following data were extracted for analysis:

- total number of deaths each year
- type of CCR
- CCR brand
- mechanical control or electronic control
- cause of death
- equipment-related
- risk-related
- unrelated to CCR
- unknown.

Discussions with training agencies and manufacturers provided a very rough estimate of the total number of CCRs thought to be in use worldwide (denominator).

The RBW website was accessed and the number of registered users for the various types of CCRs was extracted. This was then compared to the total number of registered users.[3] RBW has approximately 30,000 users of whom 1,554 had 'registered' their type of rebreather at the time of access. These proportions were then compared to similar information from a survey of Dutch CCR users conducted in 2009.[4] Comparison was made of the proportions of various brands of CCRs in use and the proportions of mechanically controlled CCRs (mCCR) relative to electronically controlled CCRs (eCCR).

Mortality data associated with CCR use were obtained from the *Deeplife* database, a British Sub-Aqua Club (BSAC) study covering 1998 to 2009 and the DAN-Asia Pacific (DAN-AP) Australasian diving mortality database.[2,5,6] Mortality data from recreational scuba diving and other sporting activities were obtained from a variety of sources in order to provide a comparator.[7–11]

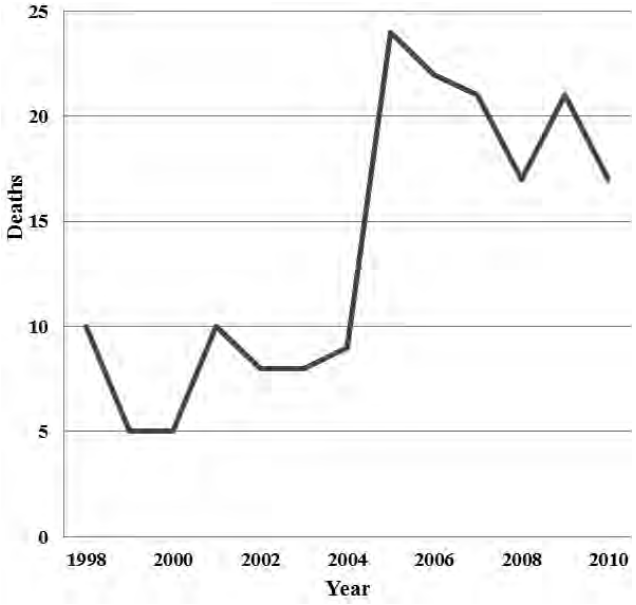
For each case in the database where there was sufficient information to determine a cause, a risk rating from 1 (least risk) to 5 (most risk) for the dive was allocated:

1 low risk, < 40 msw, all checks and tests conducted, no wreck/cave penetration;
2 moderate risk, < 40 msw, all checks done, wreck or cave penetration performed;
3 intermediate risk, > 40 msw, all checks completed;
4 high risk, > 40 msw, all checks and tests done, wreck or cave penetration;
5 extreme risk, > 150 msw or checks not done or alarms ignored.

These data were then compared to a survey conducted in 2002 by Steven Hawkins of users of the Inspiration™ eCCR.[12]

Finally, failure probability trees were constructed using the method described by Stone to attempt to determine the relative risk of mechanical failure of a CCR compared to OC scuba.[13] Further 'fault trees' were constructed for each of the major sub-systems of the CCRs to outline the myriad of potential causes of failure and the multiple corrective measures possible, as well as to demonstrate the relative importance of the various corrective strategies.[14]

Figure 1
Recreational closed-circuit rebreather deaths by year 1998–2010



Results

Between 1998 and 2010, 181 deaths were recorded in the corrected *Deeplife* database. There was a peak of 24 deaths in 2005, which seems to have been something of a watershed year. Prior to 2005, deaths had averaged eight per year, while after 2005 there were, on average, 20 deaths per year.

Between 1995 and 2011, the three major US-based training agencies conducted approximately 18,000 entry-level rebreather certifications with approximately 1,400 per year being conducted between 2001 and 2011.[15] Intermediate and advanced level certifications were achieved during the same period (2001–2011) at approximately half the annual rate for basic certifications (i.e., approximately 500 per year each). Based on these data, discussions with informed members of the diving industry and the data extracted from the RBW website, it was estimated that in 2010 there were approximately 14,000 active CCR divers worldwide.

Based on survey data, it was estimated that an average of approximately 30 dives per year per CCR diver were performed, with most active divers conducting between 20 and 50 dives each year.[3,12] At an annual death rate of 20 divers per year, this equates to an estimated death rate of 4 per 100,000 dives per year or approximately 10 times that of non-technical recreational OC scuba diving.[6–8,10,16]

The causes of the 181 fatalities are listed in Table 1. Of the total of 181 deaths, 57 (31.5%) had insufficient data to form

Table 1
Recreational closed-circuit rebreather deaths by stated cause; note the large number of cases in which there is scant information; in many other cases, while a cause of death is given, little evidence is available to corroborate that analysis

Cause of death	Number	%
Hypoxia	31	17
Hyperoxia	7	4
Hypercapnea	17	9
Acute myocardial infarction	15	8
Arterial gas embolism	12	7
Pulmonary barotrauma	6	3
No training	2	1
Drowning	5	3
Inert gas narcosis	4	2
Entanglement	1	1
Other	24	13
Scant data	57	31
Total:	**181**	

any conclusions; 80 (44%) were attributed to equipment-related problems; 43 (24%) to diving-related problems and the remainder were a mixture of problems such as acute myocardial infarction, loss of consciousness from diabetes mellitus, etc. In the BSAC data (27 deaths), there were scant data in seven cases and 14 cases were associated with either "*equipment failure*" (four cases) or the unit not being turned on correctly (11 cases). In only five cases was the cause of death thought to be unrelated to the type of breathing apparatus in use.

Each brand of CCR in use was represented in the mortality figures roughly in proportion to its market share from 2005 on. Analysis of data prior to 2005 was not performed as only one recreational CCR, the Inspiration™ (Ambient Pressure Diving®, Cornwall UK), was available up to this time. The only major brand not represented in these mortality data is the rEVO® (Paul Raymaekers, Belgium) which, while holding a significant market share from 2010, had, at the time of analysis, not been associated with any deaths. However, fatalities on this unit have been reported since this analysis was made.

Comparing the brand market share in the *Rebreather World* group to that of the Dutch survey, there is an apparent over-representation of CCRs that hold a CE certificate (Conformité Européene; i.e., compliance with European Union legislation and testing) in the latter, presumably because in Europe there is a requirement for CCRs to hold this certificate before they can be sold commercially. Nevertheless, given the broad confidence intervals of the data from the *Deeplife* database, the mortality by brand is comparable in these two data sets.

In the RBW survey, mCCRs represented 22% of units, while in the Dutch survey, the proportion was 15% mCCRs,

Table 2
Recreational closed-circuit rebreather risk behaviour index vs. mortality (see text for explanation; cases with sufficient data)

Risk rating	# cases	%
1	41	33
2	7	6
3	42	33
4	24	19
5	12	10
Total:	**126**	

accounting for 20% of deaths overall and 16% of deaths after 2005, roughly in proportion to their usage. The type of rebreather being used was not available in the BSAC data.

If a risk rating is applied to the cases in the database with sufficient information (n = 126) using a similar methodology to Hawkins, then two-thirds of cases would appear to be associated with high-risk behaviours (Table 2).[12]

Discussion

The numbers of active rebreather divers worldwide are difficult to estimate and any such estimates can only be approximate. Manufacturers are unwilling to divulge the numbers of units sold, perhaps because of concerns about potential litigation if their unit were to be associated with a high proportion of accidents and deaths. Furthermore, for units such as the Inspiration™ that have now been available for more than a decade, the number of units sold will no longer represent the number of units in active use. Without a good estimate of the total number of rebreathers in active use, the risk associated with each unit or user is difficult to quantify and, even if manufacturers were to reveal the number of units produced, this would not account for the number of scrapped units, units not in active use, nor the number of dives done per year per unit.

Various estimates of fatality rates have been suggested, ranging from one in 10 users (Heinerth J, personal communication during a television documentary, period not specified),[15] to 360 per 100,000 divers per year, based on 20 deaths per annum and 5,000 units in regular use.[16] Others have suggested the total number of rebreather divers lies between 5,000 and 15,000 worldwide.[11,15] The data on CCR certifications beyond the initial training skill level would tend to indicate a high retention rate of CCR divers.[16] This is not altogether unexpected given the high purchase costs of CCRs and the commitment required to perform this type of diving. These figures do not include certifications from BSAC or SSI, two agencies assumed to have certified technical divers in Europe, the UK and Australasia for several years.

Assuming (as in the results section) 14,000 CCRs in current use and that CCR divers conduct approximately 20–50

Table 3
Comparison of fatality rates of various high-risk sports

Sport	Death per activity	Deaths per 100,000 activities
Base jumping	2,317 jumps	43.16
CCR diving	18,750 dives	5.33
Sky diving	101,000 jumps	0.99
Hang gliding	116,000 flights	0.86
Horse riding	175,418 rides	0.57
Scuba diving	200,000 dives	0.50

dives per year, one can calculate a mortality rate of between 3/100,000 dives and 7/100,000 dives, approximately 10 times that for recreational OC scuba diving.[4–8,10,12,17] If confidence intervals in arriving at these figures were able to be constructed, they would be expected to be very wide indeed. If a mortality rate of 5 per 100,000 dives was proven to be correct, this would make CCR diving approximately five times more dangerous than hang gliding and 10 times more so than horse riding, although 8 times less dangerous than base jumping (Table 3)![8]

BSAC data from 1998–2010 would indicate that CCR divers in the UK were approximately four times more likely to be involved in a fatal accident than open-circuit divers, representing 14% of fatalities but only 4% of dives. These are probably some of the more robust data available but must be considered in the context of the small numbers involved. It is also interesting to note that in these data 38% of deaths were associated with diving to depths greater than 40 msw, independent of the equipment used. Diving beyond 40 msw represented 11% of dives in this study, equating to a three-fold increase in risk of death associated with increased depth alone. If we assume the majority of CCRs are used for deep, mixed-gas diving this raises the issue as to what extent the breathing apparatus itself is responsible for increased risk and to what extent it is a function of a dangerous (deeper) environment. In the BSAC mortality data for OC diving, there were 13 cases of equipment failure in OC divers and 36 cases (24%) where the victim ran out of gas, a rare problem with CCR divers.[5,9] Despite the perceived simplicity and reliability of OC diving equipment, almost 9% of the deaths were attributed to equipment failures. This compares to approximately 30% attributed to CCR equipment failure in the *Deeplife* database.

When CCRs first became available to recreational divers, they were largely limited to 'high-end' technical divers conducting deep, mixed-gas expeditionary dives. Not surprisingly, with new technology in the hands of civilians who were accustomed to conducting high-risk dives, deaths began to be reported soon after.[2] The attitude at that time was exemplified by photos of some of these divers on the wreck of *HMHS Britannic* at 110 msw without any visible OC bailout.[18] A survey of registered Inspiration™ CCR users conducted in 2002 identified high-risk behaviours in CCR divers, such as continuing with the dive or commencing the dive with alarms sounding or entering the water with one or other gas turned off.[12] Divers were allocated a 'risk rating' score of 0–9 based on these behaviours. Divers who reported a score of 9 subsequently had a greater than 80% two-year mortality.[19]

There was a sudden doubling of the number of annual rebreather-associated deaths in 2005. It is unclear whether this was associated with a sudden increase in the variety of units becoming available or a sudden adoption of CCRs by the wider diving community. Anecdotally, CCR divers were much more commonly seen on commercial dive boats after this time, but data from the major US-based training agencies does not show any sharp increase in numbers of certifications at or just before this time. From an Australian perspective, all the recorded deaths have been after 2005 and, while the numbers are thankfully small, they would seem to reflect the broader pattern of deaths, with one from entrapment (unrelated to the type of scuba), one from narcosis (diving-related) and one each from hypoxia and hyperoxia (CCR-related). In the latter two cases, lack of training and experience played an important role.[6]

The author's experience as a medical advisor to the DAN-AP Australian diving mortality study has emphasized the difficulty of ascertaining causality in diving deaths from the limited information that is often available, even with access to police and coronial service records. The information in the *Deeplife* database by comparison is often uncorroborated and scant in its detail. As such, the associated accident analysis must be undertaken in a very guarded fashion. However, certain types of cases do seem to appear rather more frequently. In particular, cases of divers attempting very deep dives with limited experience and divers continuing to dive despite the CCR alarms indicating problems with the unit seem to recur in reports. Despite more than a decade of warnings, the dangers of overconfidence do not seem to have been taken to heart by many new CCR divers. Furthermore, there have been a number of near misses reported on RBW forums that seem to arise from misinformation promulgated via the internet. These issues continue to be a challenge to those who wish to promote safety in this area.

While it would appear that some (indeed, much) of the increased mortality associated with CCR use may be related to high-risk behaviour and the risks of diving at depth, the complexity of CCRs means that they are by nature more prone to failure than OC equipment. In his analysis of mechanical failure risk on the Wakulla Springs Project, Stone derived 'failure trees' for various equipment configurations.[13] In this model, the risk of system failure in a linear system, such as a standard OC scuba system, is the result of the addition of the probabilities of the failures of individual components. If a parallel or redundant system can be introduced, then the probabilities are multiplied, resulting in a substantial reduction in overall risk. His modelling suggests that by using a manifold twin-cylinder

Figure 2
Probability failure tree for a standard open-circuit scuba system

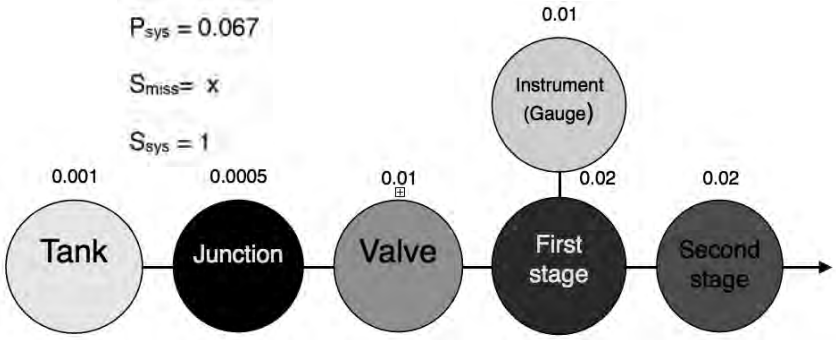
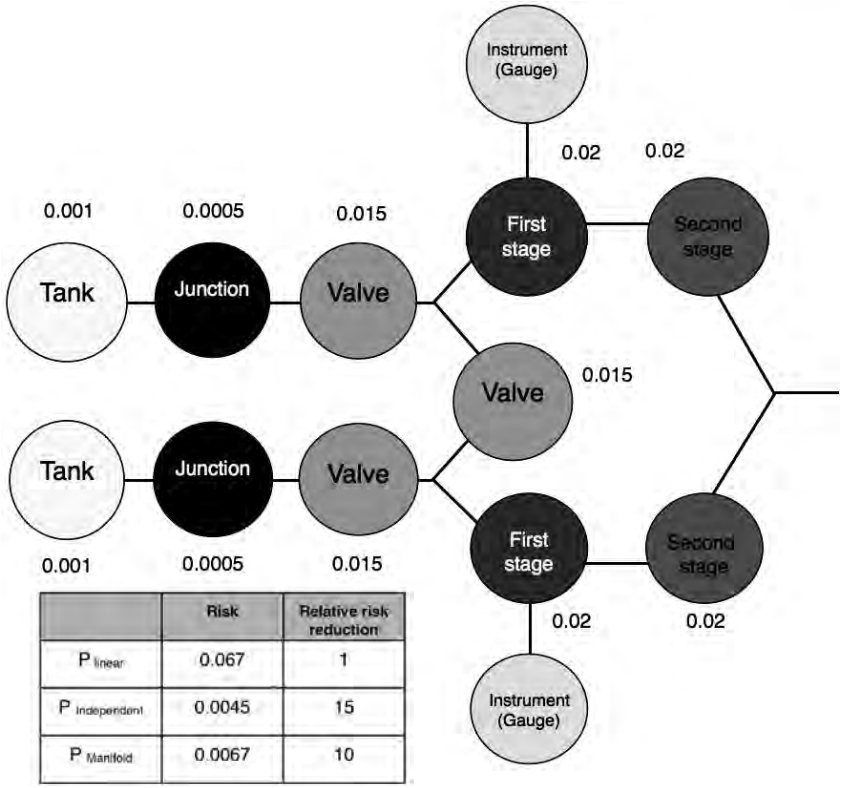


Figure 3
Probability failure tree for open-circuit manifold twin cylinder



	Risk	Relative risk reduction
P_{linear}	0.067	1
$P_{independent}$	0.0045	15
$P_{Manifold}$	0.0067	10

OC configuration the risk of mission-critical failure could be reduced by eleven-fold, whereas reduction in the risk of a single component only resulted in a small overall reduction in risk (Figures 2 and 3).

When such modelling is applied to CCRs, the risks of purely mechanical failures result in a theoretical overall risk increase of failure of 23 times compared to a manifold twin-cylinder OC (Table 4). Redundancy in some subsystems can reduce this risk of failure, particularly in key areas such as electronics. Indeed, where the CCR has two redundant computers with twin redundant batteries, the overall risk of failure of the unit is actually less than that of the simpler mCCR, with its single O_2 display. Further, the ability to 'plug-in' off-board gas via a totally independent mechanism, as exists on some CCRs, reduces the overall risk of mission-critical failure by three-fold.

For the purposes of the analysis, the assumption is made that a single-point failure in a CCR is mission-critical, unless there is a redundant system. While for OC scuba this is true, for many CCR failures the failure of a single subsystem may not result in the need to seek an alternate source of breathing gas. An example of this type of failure is the loss of all diluent when at depth. Diluent is not required during the bottom phase or during ascent, therefore, loss of this gas would not require the diver to 'bailout' to an alternative source of breathing gas, and ascent could be conducted as per normal on the CCR.

Table 4
Recreational closed-circuit rebreather (CCR) mechanical failure analysis: probabilities for linear systems are additive and those for redundant systems multiplied; note the overall very low probability of computer failure where there is a redundant computer and battery arrangement

Subsystem	*P* for component failure	*P* for critical failure
Electronics		
Battery	0.05	0.003*
Computer	0.01	0.0001
Oxygen cells	0.02	0.0004†
Total:		**0.003**
Gas O_2		
Tank	0.01	0.001
Junction	0.005	0.001
Valve	0.015	0.015
First stage	0.02	0.02
Gauge	0.01	0.01
Manifold	0.005	0.005
Manual add	0.015	
Solenoid	0.03	0.0005
Total:		**0.52**
Gas diluent		
Tank	0.01	0.001
Junction	0.005	0.001
Valve	0.015	0.015
First stage	0.02	0.02
Gauge	0.01	0.01
Manifold	0.005	0.005
Manual add	0.015	
ADV	0.02	0.0003
Total:		**0.61**
Loop		
Scrubber	0.01	0.01
Hoses	0.02	0.02
DSV	0.01	0.01
Total:		**0.04**
eCCR with no bailout failure probability		0.156
OC twin-cylinder system failure probability		0.007
Relative Risk CCR/OC: 23		

* 2 batteries; † 2 cell failure

Table 5
Recreational closed-circuit rebreather (CCR) vs. open-circuit (OC) decompression dive risk analysis (OC diver requires two stage cylinders to complete decompression schedule): risk of mechanical failure comparable as the CCR diver carries a redundant scuba system (bailout) while the OC diver must use each of his cylinders for the dive; in practice, OC divers reduce this risk by calculating to have 1/3 of gas in reserve in each cylinder and diving in a team

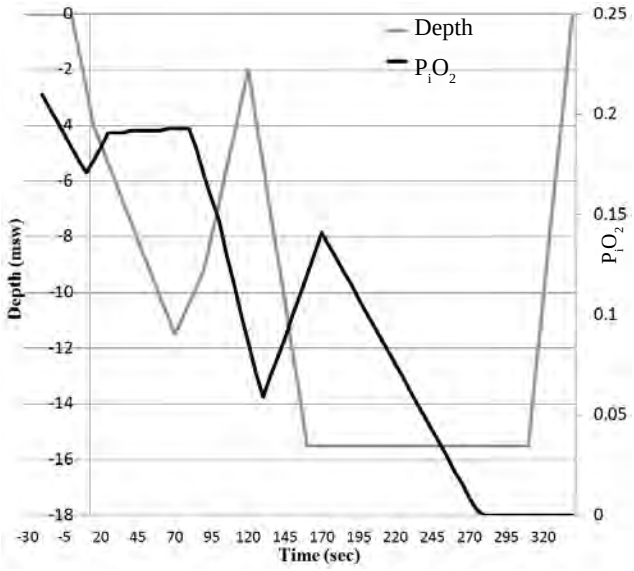
OC scuba	*P* subsystem failure
Risk manifold system failure	0.007
Risk Stage tank 1 failure	0.067
Risk Stage tank 2 failure	0.067
Risk mission critical failure	0.140
(Probabilities are additive)	
eCCR + 2 OC bailout cylinders	
Risk eCCR failure	0.156
Risk bailout tank 1 failure	0.067
Risk bailout tank 2 failure	0.067
Risk mission critical failure	0.021
(OC risk probably additive, CCR/OC risk multiplied)	
Relative risk eCCR versus OC scuba	0.15

The assumption that CCRs are less mechanically reliable is widely held, and most CCR divers carry OC cylinders for 'bailout' in case of CCR failure. In contrast to OC divers conducting decompression dives, where the cylinders form part of the decompression gas requirements, these cylinders represent a redundant scuba that is not used except in emergencies. When the presence of a redundant scuba is included in the failure risk calculations and compared to an OC diver conducting a decompression dive with two decompression gases, then resultant risk of overall mission-critical equipment failure becomes similar (Table 5). This is predicated on the CCR diver having ample gas to complete the dive using the OC gas carried. For deeper dives where logistics dictate that carrying complete bailout is impractical, divers will often utilizes a buddy system for bailout. This again is predicated on the buddies staying together rather than adopting the 'same ocean' buddy system conducted by some technical divers! It is interesting to note that, in this purely mathematical analysis, buddy diving offers a reduction of risk of almost an order of magnitude, strongly supporting the proponents of this behaviour.

There are few or no data on the actual mechanical failure rates of either OC scuba or CCRs. However, personal experience would indicate that mechanical failure of OC scuba is a rare event. While the theoretical risk of mechanical failure of a CCR is certainly higher than for a manifold OC twin-cylinder arrangement, the overall risk of failure in a correctly maintained and checked CCR system would still be expected to be low overall. Nevertheless, failures are commonly reported on internet forums. In an analysis of human factors in CCR failures, more than half the failures were attributed to poor training or poor pre-dive checks.[14] The experienced OC diver who takes up CCR diving was identified as being at particular risk of overestimating their ability. With OC scuba systems, there is usually only one correct response to failure. The complexity of CCR diving and the interaction of physics, physiology and equipment mean that there may be many possible responses that allow the diver to continue breathing, not all of which will result in a successful outcome. The following case is illustrative (Figure 4).

This diver entered the water with his CCR turned off. The diver had pre-breathed the unit before entering the water,

Figure 4
Dive depth and inspired oxygen partial pressure profile of a fatal recreational closed-circuit rebreather dive; unconsciousness occurs 130 sec into the dive due to ascent hypoxia and failure of oxygen addition because the unit had not been turned on



but for insufficient time for the PO_2 to fall to a critical level. Descent resulted in an increase in PO_2 despite the consumption of O_2 from the loop. At approximately 14 msw, the diver became aware the CCR's electronics were not turned on. Options at this time included:

- bailout to OC scuba;
- ascent to 6 msw and flushing the CCR with O_2 to provide a known breathing mix that was non-hypoxic on the surface;
- turning on the electronics (not recommended as the unit would attempt to calibrate the O_2 cells underwater; however, possible if the correct sequence was followed).

While the PO_2 in the breathing loop of the CCR at 14 msw was still 0.2 atm and hence quite breathable, an understanding of physics and physiology would have told the diver that ascent without the addition of O_2 would result in a rapid fall in the PO_2 in the breathing loop. This diver was a very experienced OC diver and his first reaction was to return to the surface to correct the problem. As one might predict, he became unconscious from hypoxia just below the surface and drowned. The entire event occurred in less than 150 seconds from the commencement of the dive.

In this case, there was nothing wrong with the CCR, rather, the failures were in the pre-dive checks to show the CCR's electronics were turned off and in undertaking insufficient pre-breathe time. This type of problem may occur where the diver has completed the standard checks and then the dive is delayed for a short time while some adjustment is made, e.g., the shot line is re-sited. The diver may respond by turning off the unit in a misguided attempt to save battery life, and then fail to turn it back on in the distraction of 'getting on with the dive' subsequently. The situation was eminently salvageable without the need to go 'off the loop', but a failure to understand the consequences of the various options resulted in a tragic outcome.

The use of basic check-lists and of 'good design' have been advocated to eliminate wherever possible the chance of human error.[14] Such design should:

- minimize perceptual confusion;
- make the execution of action and response of the system visible to the user;
- use constraints to lock out the possible causes of errors;
- avoid multimodal systems.

Training should provide for acquisition of basic skills so that these become 'hard-wired', thereby allowing clear mentation in times of stress while making critical decisions.

One potential method of providing this would be to stage rebreather training such that initial certification did not allow for decompression diving and only allowed for limited failure response in a way similar to OC diving, e.g., OC bailout as the only option. Only once the actual CCR diving skill set and basic CCR management was well ingrained would more complex teaching concerning rebreather physics and physiology be introduced in conjunction with discussions on alternative bailout options and decompression diving.

Conclusions

In the period from the introduction of the first mass-market CCR in 1998 to 2010, there have been 181 reported deaths. While the number of rebreathers in use remains unknown, best-guess figures suggest that using a CCR is associated with a four- to ten-fold increased risk of death compared to recreational OC scuba diving. Some of this risk may be associated with the use of CCRs for higher-risk deep diving, which in itself is associated with a three-fold increase in risk of death. Two-thirds of the reported deaths appear to have some association with high-risk behaviours including commencing or continuing dives with alarms activated or with known faults to the CCR.

There does not seem to be any particular brand of CCR over-represented in the mortality data and, despite popular perception, mCCRs are not associated with a lower mortality than eCCRs.

CCRs have an intrinsically increased risk of mechanical failure because of their complexity; however, this risk is probably small, and many of the failures seen appear to be related to training issues, failures of maintenance and failure to conduct adequate pre-dive checks. While good design can help reduce the chance of human error in maintenance and pre-dive assembly, the major emphasis should be on reducing human error, including modification of high-risk behaviours. Modifications to training, education and certification of CCR divers may be one way of achieving this.

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Andrew W Fock, MB BS, FANZCA, Dip DHM, is Head, Hyperbaric Service, Department of Intensive Care and Hyperbaric Medicine at the Alfred Hospital, Melbourne.

Address for correspondence:
Andrew W Fock MB BS, FANZCA, Dip DHM
Head, Hyperbaric Service
Department of Intensive Care and Hyperbaric Medicine
The Alfred Hospital
Commercial Road
Prahran, Victoria
Australia
***Phone**: +61 3 9076 2269*
***E-mail:** <a.fock@alfred.org.au>*