IN THE LOOP

RF3

REBREATHER FORUM 3

POWERED BY

REBREATHER FORUM 3 PROCEEDINGS

18 - 20 MAY 2012

Caribe Royale Hotel, Orlando, Florida, USA

Editors

Richard D. Vann

Petar J. Denoble

Neal W. Pollock

www.rf30.org

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Photo by Jill Heinerth

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TABLE OF CONTENTS

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Rosemary E. Lunn wishes to acknowledge and thank the event team and the following personnel for their assistance and support with organizing Rebreather Forum 3: Jason Brown (Bardo Creative), Terry Cummins (PADI), Pattie Haught (Divers Alert Network), Dali Mearns (Light Monkey), Jim Standing (Fourth Element), Peter Symes (X-Ray Magazine) and Edward Williams (Divers Alert Network).

Thanks are also extended to Niles Clarke for proofreading, Diana Williams Palmer for editing and Rick Melvin for production layout.

FORWARD

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The theme of Rebreather Forum 3 (RF3) was innovation, technology, exploration, adventure, and safety. This was a safety meeting, a state-of-the-art meeting, and a planning meeting. We reviewed the collective experience of all user groups, exchanged ideas, examined equipment, and refreshed our thinking since Rebreather Forum 2 (RF2) in 1996.

The goals of RF3 were to:

- further rebreather diving safety;
- reduce incidents among all rebreather diver groups;
- advance the state of the art and use of the technology;
- improve human factors in rebreather diving;
- expand access to rebreathers among the various diver groups as appropriate; and
- provide a common information foundation for the rebreather diving community.

The objectives of RF3 were:

- Establish the state of the art, practice, experience, and knowledge such that the culture of rebreather diving might be beneficially changed. What are the specific factors that cause problems, and how might they be prevented?
- Based on collective experience, unbiased reason, and common sense, what changes might be proposed to avoid problems and take advantage of identified safety enhancements?
- How might what was learned in each session be integrated to work together as a whole?
- Publish proceedings describing the state of practice for rebreather technologies, and identify the most common causes of rebreather incidents, explaining the technical, training, and operational characteristics that do or could reduce rebreather incidents for user groups.

Definitive evidence and objective reason were emphasized as the basis for credible hypotheses, while opinion and speculation were discouraged.

Most of the oral presentations at RF3 were submitted as manuscripts and appear in this publication. Michael Menduno reviewed the history of rebreathers, indicating progress since RF2 and citing unfinished business. Simon Mitchell provided a primer in rebreather diving and a detailed review of rebreather physiology. Jerry Whatley described the new Rebreather Educational and Safety Association (RESA) that brings together the principal industry organizations to address issues of common interest. Rebreather communities have evolved unique characteristics that were described by CDR Mike Runkle (military), Christian McDonald (scientific), Evan Kovacs (video), Mark Caney (recreational), Phil Short (technical), and Lamar Hires (cave). Harry Harris discussed rebreather applications for remote exploration. Mark Caney and Nancy Easterbrook led panels on business and travel with rebreathers. Neal Pollock discussed thermal protection, while David Doolette discussed decompression. John Clarke reviewed semiclosed rebreathers.

Dan Orr and Petar Denoble reviewed the experience of Divers Alert Network (DAN) with open-circuit and closed-circuit diving fatalities. David Concannon described the state of rebreather fatality investigations, and Dick Vann led a panel on U.S. Coast Guard investigations. Andrew Fock presented tentative conclusions from investigation data, and Martin Parker discussed how rebreather data stored in "black boxes" can contribute to fatality investigations. Bill Stone discussed hazard analysis and how rebreathers might be engineered for greater safety, and Rich Pyle offered a blueprint for accelerating progress in rebreather diving effectiveness and safety.

Arne Seiber and Nigel Jones independently discussed new developments in oxygen control and sensing. Kevin Gurr and Dan Warkander presented assessments of carbon-dioxide monitoring and control. Gavin Anthony and Mike Ward discussed premarket rebreather testing from the European and United States perspectives, while Oskar Franberg and Vince Ferris described postfatality testing from Swedish and U.S. Navy experiences. Richie Kohler and Jill Heinerth offered their personal perspectives on what divers might do raise their own levels of safety (CHECKLISTS!). Joe Dituri, Brian Carney, and Ed Betts pooled rebreather training data in a cooperative effort to estimate rebreather certifications from 1990 to 2011.

Last, Jeff Bozanic and Jill Heinerth led discussions concerning rebreather operations and rebreather training, and Simon Mitchell refereed a discussion of the key consensus items raised through the meeting.

BUILDING A CONSUMER REBREATHER MARKET: LESSONS FROM THE TECHNICAL DIVING REVOLUTION

Dedicated to Dr. R.W. "Bill" Hamilton (1930-2011), who helped guide the sport-diving community through many difficult issues while balancing the importance of exploration with the need for diver safety.

Michael Menduno
Journalist and Technologist
Cathedral City, CA, USA

ABSTRACT

The history and development of consumer rebreather technology is examined as a key component of the so-called "technical diving revolution," which brought mixed-gas diving technology to the sport-diving community. Lessons learned by early technical divers are reviewed, and how these informed the subsequent rebreather development is summarized. Findings and recommendations of the original 1994 Rebreather Forum and 1996 Rebreather Forum 2.0 (co-organized by the author) are assessed for progress and areas where work is still needed. Finally, interviews with industry insiders highlight some critical issues to be addressed if rebreather technology is to reach a broader consumer diving market.

Keywords: diving safety, nitrox, rebreather forum

INTRODUCTION

Today, no matter where you travel, nitrox diving is ubiquitous. In fact, it is PADI's best-selling course outside of open-water diving. Similarly, most sport divers know about the use of helium for deep diving, oxygen for decompression and argon for drysuit inflation. Though the number of rebreather units in the field is tiny compared with the number of open-circuit scuba sets, most divers are aware of rebreather technology and likely have seen it on TV. The situation was completely different 25 years ago when these technologies were just being introduced to sport diving in what became known as the "technical diving revolution." (The term "technical diving" was first used by *aquaCORPS* #3 MIX, January 1992, to refer to this emerging segment of sport diving.) It was a time when "air diving" was diving, 130 ft (40 m) was deep and decompression diving — the D-word — was a four-letter word.

I was fortunate to witness and report on the emergence of technical diving in the late 1980s and early 1990s through my magazine *aquaCORPS*. Rebreathers were a key part of that development. In fact, in many respects you could say that the recent emergence of the "consumer" rebreather designed for recreational divers represents the ultimate goal and fulfillment of the technical-diving revolution, which served to greatly expand our underwater envelope and redefine the business of sport diving.

I propose that rebreather technology, which was first conceived in the 17th century by Giovanni Borelli, has gone through a series of technological inflection points over the past 50 years, each one resulting in an expanded base of rebreather users. These inflection points began with the development of the first electronically-controlled, closed-circuit rebreathers (CCR) in the 1960s, which resulted in their adoption by military divers, the "reintroduction" of rebreathers to the sport-diving community (actually technical divers) in the late 1980s, and the release of the first consumer production units in the mid-to-late 1990s, coinciding with Rebreather Forum 2.0, which I organized in 1996 with rebreather developer Tracy Robinette, owner of Divematics Inc. Today many industry participants

Figure 1. One of the earliest "rebreather" designs. In 1680 Giovanni Borelli envisioned a diver carrying a large bag of air from which the diver breathed, as necessary. Image courtesy of Cayman Island Twilight Zone 2007 Exploration, Giovanni Borelli 1680, Library of Congress, July 1, 1909, NOAA-OE.

believe that the technology is poised at another inflection point as rebreathers, which until now have been used almost exclusively by the technical-diving and scientific communities, are being introduced to recreational divers.

I will discuss each of these inflection points, their lessons, and identify and frame some of the issues surrounding rebreather technology that still need to be addressed if the technology is to grow and reach a broader consumer market.

TO GO WHERE NO ONE HAS GONE BEFORE

I would like to begin with a quote from one of our great explorers, the late Sheck Exley, who summed up his drive to explore underwater caves this way (*aquaCORPS* #3 MIX, January 1992, "Exley on Mix," by Michael Menduno):

Figure 2. Sheck Exley at Nacimiento del Rio Mante

"There are places that no one has been to since the dawn of time. We cannot see what is there. We can see what is on the dark side of the moon or what is on Mars, but you cannot see what is in the back of a cave unless you go there. There is a special feeling when you know no one has been there before and an extra special feeling when you know no one has ever been that far. I enjoy that feeling."

I think it is fair to say that without this genetic disposition to explore, we would not be here today attending Rebreather Forum 3 (RF3) nor would there likely be any sport-diving rebreathers. And it is not just explorers who are subject to this impulse. I believe recreational divers are drawn by this same urge when they descend on a reef or a kelp forest for the first time, or the 10th, and in doing so are vicariously able to touch the wilderness that surrounds us.

This need to "go where no one has been before" was certainly a driving force in the 1980s, which was a time of intense underwater exploration, particularly in the cave-diving community. It was not uncommon at the time for explorers to be conducting 200- to 300-foot (61- to 91-meter) or more dives on air, using oxygen for decompression, at their own peril. Needless to say, the details of many of these dives were kept secret by the individuals involved, less the innocent be led to slaughter. Even in the cave community, where these dives were more or less accepted as necessary to push back the frontier, there were no guidelines for diving beyond 130 ft (40 m).

Driven by the need to go deeper and stay longer — a fundamental theme that runs through the history of diving — small groups of experienced divers led by pioneers such as Dale Sweet, Jerry Buchanan, Jochen Hasenmayer, Sheck Exley, Bill Gavin, and others, began experimenting with mixed-gas technology to push the limits of self-contained diving still further. (Dale Sweet made the first successful "amateur" mix dive at Diepolder 2 in 1980. See "Mix Timeline," *aquaCORPS* #13, O_2/N_2.) It seems remarkable now that explorers such as Exley were conducting mixed-gas dives as deep as 600 ft (183 m) to nearly 900 ft (274 m) in the mid- to late-1980s before most of the recreational community could even spell nitrox, let alone appreciate its use.

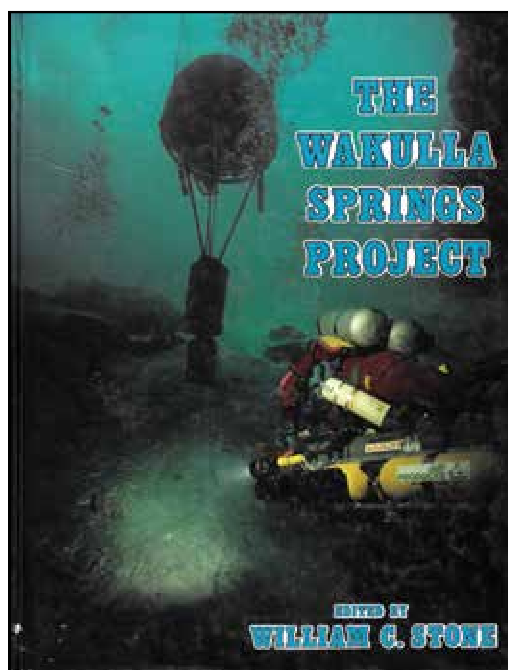


Figure 3. Wakulla Springs Project

Almost all of the early development work with mixed gas was conducted by the cave community. The wreck-diving community was also engaged in exploration and was pushing air limits with relatively short 15- to 20-minute dives to 200-260 ft (61-79 m). Most of these dives were conducted on air using U.S. Navy (USN) tables or dive computers, and few, if any, wreck divers were using oxygen for decompression. In many respects, the cave environment, which offers confined water and usually ample areas for staging cylinders (and decompressing) proved to be a more accessible proving ground for mix technology.

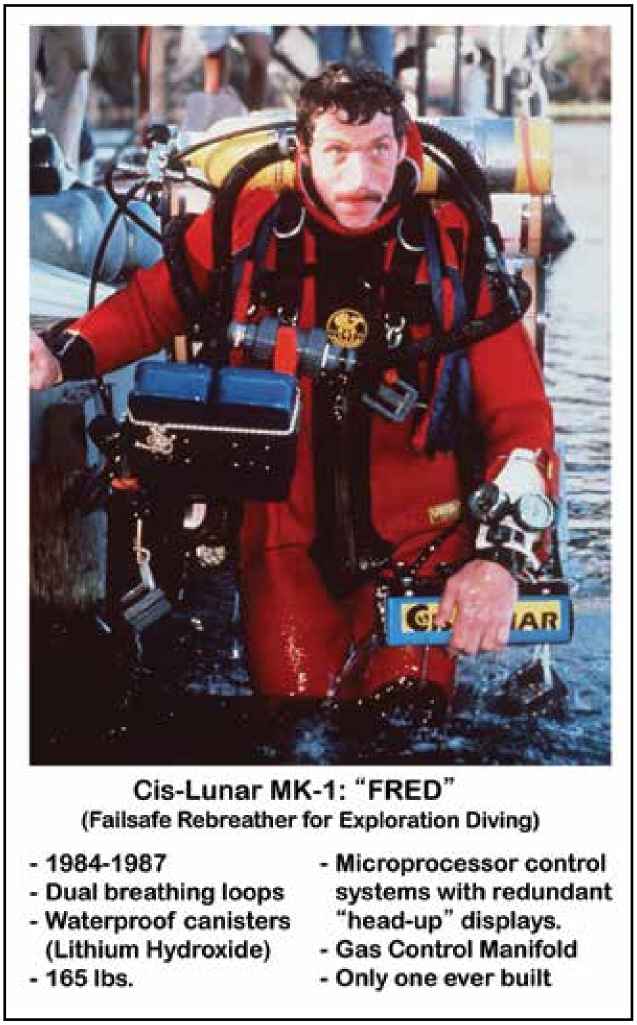


Figure 4. Bill Stone with his Failsafe Rebreather for Exploration Diving (FRED). Images credit: Bill Stone.

Arguably the poster child for mixed-gas diving at the time was the Wakulla Springs Project, conducted in late 1987 by caver and engineer Dr. Bill Stone and his team, which captured the imagination of the diving community — or at least those in the know. In two and half months Stone and company were able to map some 2.3 miles (3.7 km) of underground passageways at depths ranging from 260 to 320 ft (79-98 m), using a host of new technologies and techniques including mixed gas, high pressure cylinders, long-duration scooters and an underwater decompression habitat. By comparison with sport diving at the time, Wakulla seemed like the equivalent of an underwater "moonshot" (Stone WC. The Wakulla Springs Project, U.S. Deep Caving Team, 1989; pers comm).

Though these dives were accomplished using open-circuit scuba, Stone realized that rebreathers would eventually be needed to overcome the limitations of open-circuit logistics for caving and deep cave diving. Accordingly, Stone and his team built his 165-lb (75-kg) prototype, the MK-1 fully redundant rebreather, dubbed FRED (Failsafe Rebreather for Exploration Diving), which Stone trialed in a 24-hour-long dive.

Figure 5. Stuart Clough and Rob Palmer with MK-15 rebreathers.

Figure 6. Oliver Isler with his redundant semiclosed rebreather.

In Europe, cave explorer Olivier Isler teamed up with engineer Alain Ronjat to build the RI 2000 semiclosed rebreather, which he used to push the La Doux de Coly siphon in 1989 (Isler, 1993). Similarly, Stuart Clough, principal of Carmellan Research, and explorer Rob Palmer, with the help of engineer Kevin Gurr, now president of VR Technology Ltd., were using modified MK-15 military rebreathers along with open-circuit heliox to explore the Andros Blue Holes.

THE FIRST MIXED-GAS CLOSED-CIRCUIT REBREATHERS

These early efforts, arguably a technological inflection point, represent the beginning of the modern use of rebreathers by sport divers. But they were not the first people to appreciate the potential of closed-circuit rebreather technology for use by sport and other diving communities.

Underwater filmmaker Hans Haas was one of the first civilians to use non-electronic pure oxygen rebreathers, also called "recirculating diving equipment," which were developed as a result of the exigencies of World War II. They also had some following among early sport divers and spearfishermen. However, the devices were limited to about 35 ft (11 m) depth, at which point the PO_2 was 2.1 atm. This was before much was known about oxygen toxicity limits. The devices became a secondary choice to "throwaway" diving equipment (the diver's exhalation was "thrown away") such as the Gagan-Cousteau "open-circuit" aqualung, which was just in its infancy.

It was not until the early 1960s that invention of oxygen sensors made the construction of an electronic mixed-gas closed-circuit rebreather possible. Engineer and inventor Alan Krasberg, founder and owner of General Diving Systems in Aberdeen, Scotland, is credited with building the first closed-circuit mixed-gas rebreather in 1962. He went on to run the first saturation diving system for Westinghouse Corporation in 1965. (Rebreather Forum 2.0, Redondo Beach, CA; 1996).

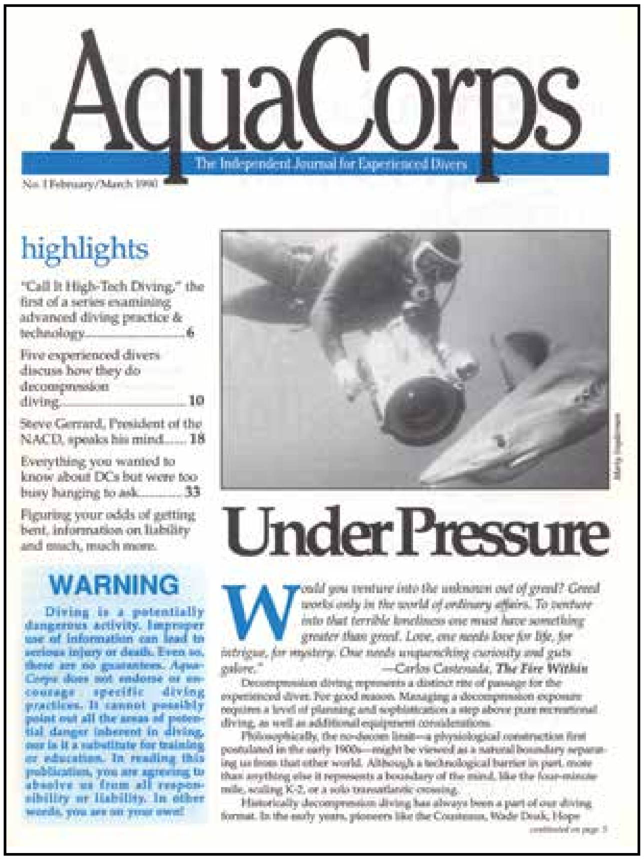
Four years later, seeing the opportunity to revolutionize sport diving, inventor Walter Starck introduced the Electrolung closed-circuit mixed-gas rebreather, designed to be used by "pro divers," i.e., experienced sport divers and instructors — the forerunners of today's tech divers — who, in Starck's words, had the "instrument sense" to use the device, which retailed for $2,000 and was advertised in *Skin Diver* magazine. Within the year of its introduction, Beckman Instruments bought the rights to Starck's entire product line and began expanding sales to government and commercial users. However, there were three high-profile sport-diving deaths: Two were ruled to be diver error, and the third was of unknown causation (Starck, 1993). Lawsuits ensued, and Beckman decided to close production of the Electrolung along with its ocean products division. The rights to the Electrolung reverted to Starck, who soon after left the U.S. for the South Pacific.

Figure 7. Walter Starck with the Electrolung.

Though sport divers would have to wait another 25 years, Krasberg's and Starck's developments helped spur a mini-boom in closed-circuit rebreathers over the next decade with units such as the Biomarine Industries CCR 1000, the predecessor to Carleton Technology's MK-15/16 used by the U.S. Navy, and the GE Model 1400 (MK-10) aimed at the military market, which was willing to take on the complexities and hazards of closed-circuit rebreathers if they enabled divers to accomplish their mission.

In parallel, a number of manufacturers sprang up to address what they hoped would be a need in the commercial-diving industry, which was faced with increasing helium costs, including the Divematics (Tracy Robinette) ShadowPac, the Westinghouse KSR-5, STM 300, Sterling Electronics SS-1000, and the Normalair-Garrett Deep Dive 500. Many of the features we see in rebreathers today, such as voting logic used in oxygen sensing, integrated bailout valves (BOVs), and heads-up displays (HUDs), made their first appearance in these early units.

Though the commercial-diving industry was initially interested and evaluated closed-circuit rebreathers for use in their diving operations, the technology was ultimately rejected as



AquaCorps

The Independent Journal for Experienced Divers

No. 1 February/March 1990

highlights

"Call It High-Tech Diving," the first of a series examining advanced diving practice & technology.......6

Five experienced divers discuss how they do decompression diving.......10

Steve Gerrard, President of the NACD, speaks his mind...... 18

Everything you wanted to know about DCs but were too busy hanging to ask.......33

Figuring your odds of getting bent, information on liability and much, much more.

WARNING

Diving is a potentially dangerous activity. Improper use of information can lead to serious injury or death. Even so, there are no guarantees. AquaCorps does not endorse or encourage specific diving practices. It cannot possibly point out all the areas of potential danger inherent in diving, nor is it a substitute for training or education. In reading this publication, you are agreeing to absolve us from all responsibility or liability. In other words, you are on your own!

Under Pressure

"Would you venture into the unknown out of greed? Greed works only in the world of ordinary affairs. To venture into that terrible loneliness one must have something greater than greed. Love, one needs love for life, for intrigue, for mystery. One needs unquenching curiosity and guts galore." —Carlos Castenada, ***The Fire Within***

Decompression diving represents a distinct rite of passage for the experienced diver. For good reason. Managing a decompression exposure requires a level of planning and sophistication a step above pure recreational diving, as well as additional equipment considerations.

Philosophically, the no-decom limit—a physiological construction first postulated in the early 1900s—might be viewed as a natural boundary separating us from that other world. Although a technological barrier in part, more than anything else it represents a boundary of the mind, like the four-minute mile, scaling K-2, or a solo transatlantic crossing.

Historically decompression diving has always been a part of our diving format. In the early years, pioneers like the Cousteaus, Wade Doak, Hope

continued on page 5

Figure 8. The first issue of aquaCORPS, *published in February/ March 1990.*

too complex and unreliable except for use in diver bailout systems for deep-water work, leaving the military-diving community as the sole users of closed-circuit technology.

ENTER *aquaCORPS*

I first got involved in deep diving through a volunteer ocean conservation group called Cordell Expeditions, founded in 1977 by Dr. Robert Schmieder in northern California. The group, which had a few dozen members, was instrumental in getting the Cordell Banks, a 42-square-mile (109-sq.-km) seamount perched on the edge of the continental shelf about 22 miles (35 km) west of the Pt. Reyes headlands just north of San Francisco, declared a National Marine Sanctuary.

I participated in their 1988 expedition doing biological surveys on the seamounts off the Big Sur coast at depths from 160-200 feet (49-61 m), after spending a few months doing work-up dives. There were no courses at the time to learn decompression diving. We conducted the dives on air using USN tables without oxygen for decompression. At the time, I had a strategic marketing consulting practice in Silicon Valley specializing in technology start-up companies, but what I really wanted to do was write about diving, and I figured that the Cordell Expedition would make a great article.

I took my story to a number of diving magazines, but no one wanted to touch it. Editors told me this kind of diving was outside the realm of recreational diving and was dangerous. They did not want to publish it. Eventually, Ken Loyst, publisher of *Discover Diving* magazine based in southern California, agreed to run the story in the January/February 1989 issue, but with a series of warnings and disclaimers practically on every page; for example: "This type of diving is beyond the realm of sport diving," or "Recreational divers should never exceed 130 ft (40 m)."

Upon doing more research, I was intrigued to learn that there were many small groups of experienced divers conducting dives that were clearly beyond the established 130-ft (40-m), no-stop diving recreational limits, but no one was talking about it for fear of perhaps ridicule and the fact that less-experienced divers could follow their example and get hurt. Likewise, the dive industry press was not writing about it. Even in communities such as cave diving, where deeper dives were accepted, there were no guidelines on what to do.

Within a year I launched *aquaCORPS: The Journal for Experienced Divers* to report on this kind of diving and introduced it at the 1990 Diving Equipment and Marketing Association (DEMA) show in Orlando, FL. I was fascinated by what was going on, and I figured that others would be as well. I remember PADI executive Al Hornsby coming to our booth with a group of PADI people and intensely staring at the sign, asking "Do you do decompression diving?" It was evident that they were not too happy. They took some copies and stormed off, shaking their heads. It was clear to me that the industry was not used to talking about these issues.

Figure 9. "Call it 'High-Tech' Diving," aquaCORPS *#1, February/March 1990.*

The cover story in our first issue was a piece by Dr. Bill Hamilton, "Call it High-Tech Diving," which explained in broad terms what was going on and some of the technologies such as mixed gas that were being used. At the time we did not know what to call this kind of diving. Obviously, it was not recreational diving, which had clearly established standards and limits.

Within a few issues, by the summer of 1991, we began referring to this kind of diving as "technical diving," a term I took from technical (rock) climbing. It seemed important to distinguish it from recreational diving so not to step on the toes of the existing dive industry establishment. The name stuck, and we changed the *aquaCORPS* tagline to *The Journal for Technical Diving*.

Regarding terminology, I know that some industry members are adamant that we refer to what we do as "recreational diving" whether we are talking about tech diving (i.e., deep diving and decompression diving) or no-stop diving no deeper than 130 ft (40 m), because the U.S. Occupational Safety and Health Administration (OSHA), which regulates the workplace, categorizes our sport as "recreational diving" and has granted it (along with scientific diving) an exemption from regulation. But I still find it important and useful to distinguish between the segments of our sport, which are, after all, very different. Accordingly, I find it more natural to categorize what we do as "sport diving" (i.e., for sport or recreation, not commerce), which is segmented into recreational diving (no-stop dives, 130 ft [40 m] or less in open water) and technical diving (generally, diving in an overhead environment).

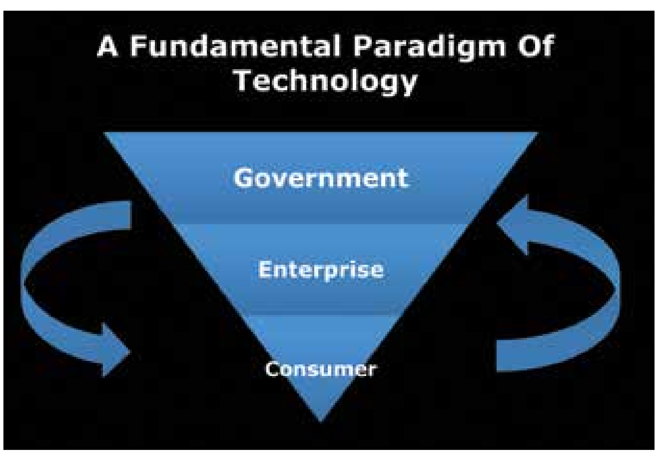


Figure 10. Technology paradigm.

CALL IT A "TECHNOLOGICAL REVOLUTION"

It seemed clear to me, coming from the computer industry, that self-contained diving was in the midst of a technological revolution that was changing the way we thought about diving, much like the personal computer was changing the world of computing. In fact, it represented a basic paradigm of technology. Emerging technologies such as computing, decompression methods, and mixed-gas technology are initially developed by governments, which have the funds to invest in the basic research and development. Then private enterprise steps in and adapts the technology for commercial use, expanding the base of users. Eventually, the technology is adapted for consumer use, which then becomes the driver for further development. We have seen this basic paradigm playing out in computing, electronics, aircraft, weapons, and a host of other areas, and that is exactly what happened in sport diving.

We called it the "technical-diving revolution," but really the revolution was about adapting mixed-gas technology, which had originally been developed by the U.S. and other governments and later adopted by private enterprise and then the consumer market. The concept was simple and brilliant: You could improve divers' safety and performance, enabling them to extend their depth and bottom time by optimizing their breathing gas for the planned exposure — that is, maximizing their oxygen levels subject to physiological constraints and selecting the right diluent for the job.

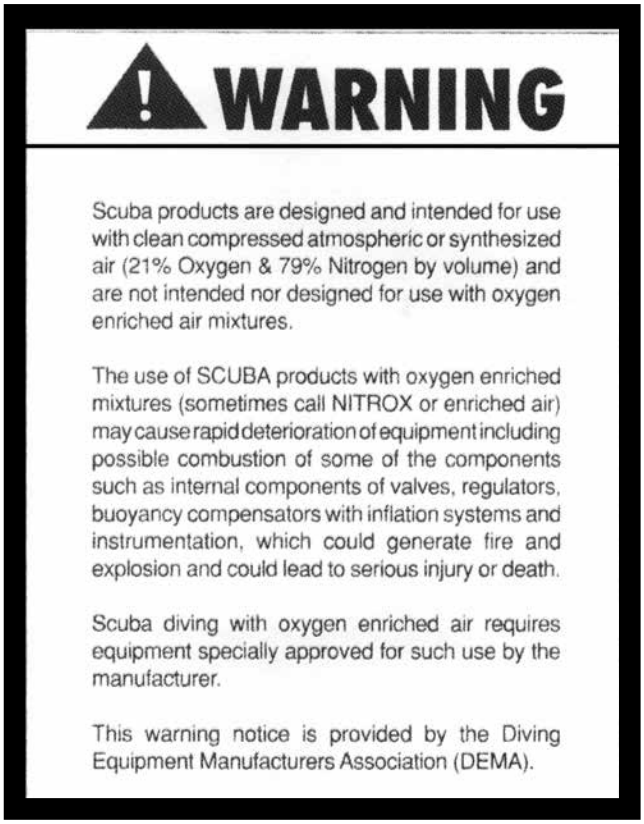
Moving to mixed-gas technology was clearly an important and necessary, though not sufficient, step for the development of rebreather technology. But it was a powerful paradigm shift because it represented a change in the diving community's worldview. As author Neil Postman (1993) wrote, "New technologies compete with old ones — for time, for attention, for money, for prestige, but mostly for dominance of their world view."

Overnight the emergence of technical diving, made possible by the use of mixed-gas technology, turned the recreational diving world on its head. While PADI "deep divers" were cautiously edging their way down to their 130-ft (40-m) limit, many tech divers were ascending to 130 ft (40 m) to pull their first decompression stop. Needless to say, recreational diving instructors no longer represented the apex predators at the top of the diving food chain.

Of course, mixed-gas technology was not only being promoted for technical divers. In addition to use by the emerging technical-diving community, Dick Rutkowski, a former aquanaut and deputy diving director for the National Oceanic and Atmospheric Administration (NOAA), founder of the International Association of Nitrox Divers (IAND) and American Nitrox Divers Inc. (ANDI), began promoting the use of nitrox for recreational diving. Not surprisingly, there was pushback from the existing dive industry establishment.

NITROX: THE DEVIL GAS

In the fall of 1991, Bob Gray, the creator and executive director of the annual DEMA trade show, decided to ban nitrox vendors and training agencies such as ANDI and IAND from attending that year's show. I later learned that the Cayman Water Sports Association along with the support of *Skin Diver*



WARNING

Scuba products are designed and intended for use with clean compressed atmospheric or synthesized air (21% Oxygen & 79% Nitrogen by volume) and are not intended nor designed for use with oxygen enriched air mixtures.

The use of SCUBA products with oxygen enriched mixtures (sometimes call NITROX or enriched air) may cause rapid deterioration of equipment including possible combustion of some of the components such as internal components of valves, regulators, buoyancy compensators with inflation systems and instrumentation, which could generate fire and explosion and could lead to serious injury or death.

Scuba diving with oxygen enriched air requires equipment specially approved for such use by the manufacturer.

This warning notice is provided by the Diving Equipment Manufacturers Association (DEMA).

Figure 11. Nitrox warning on the inside cover of the 1992 DEMA program guide.

magazine (SDM) — the association was *Skin Diver*'s largest advertiser — was behind the ban: They did not want tourist divers messing with their operation by extending their bottom times. Many heated phone calls and faxes ensued; Tom Mount, who became president of IAND and changed the name to the International Association of Nitrox and Technical Divers (IANTD), and Ed Betts, president and co-founder of ANDI, flew out to meet with Gray and get the ban lifted, which they did. That year the first page of the DEMA Exhibitor's Guide offered a warning about using nitrox with scuba equipment. Ironically, it generated enormous buzz at the show, causing attendees to ask, "What is nitrox?" This proved to be great advertising for mixed-gas technology.

While Mount and Betts were negotiating with Gray, I enlisted the help of Dr. Hamilton, and along with Diving Unlimited Inc. founder and CEO Dick Long with his Scuba Diving Resources Group and Richard Nordstrom, then CEO of Dr. Stone's company, Cis-Lunar Development Labs, organized the Enriched Air Nitrox Workshop in January 1992 in Houston, Texas, just before the DEMA show. Our goal was to bring together all the stakeholders to discuss nitrox and its uses. The result was the first set of community policies addressing the use of nitrox as well as establishing the fact that nitrox was not technical diving but rather a technology that could be used by all divers. We issued the findings from the workshop written by Dr. Hamilton in *aquaCORPS*' sister publication, *technicalDIVER*.

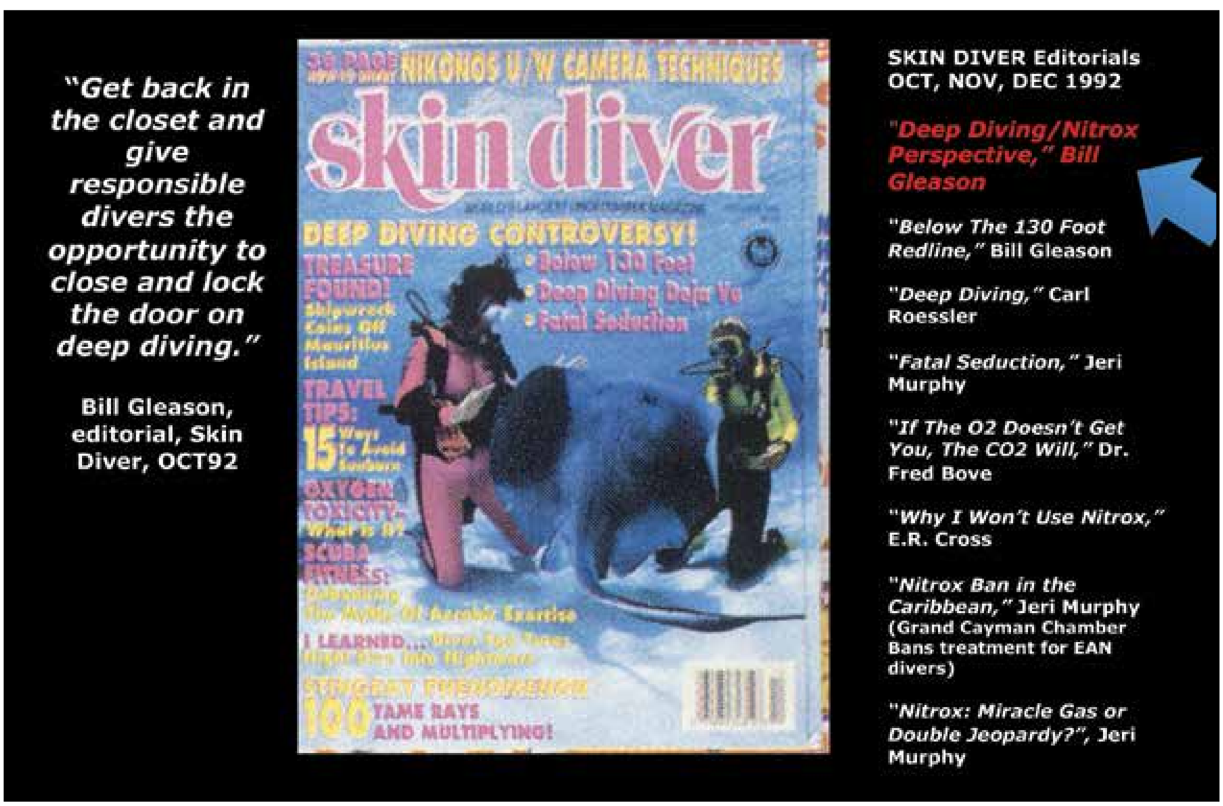


Figure 12. Skin Diver *magazine editorial.*

The summer of 1992 was a tragic one for the fledging tech-diving community. There were eight high-profile diving fatalities, including two on the *Andrea Doria* and one at the Ginnie Springs cave system in Florida, along with a number of close calls that resulted in injury. People in the community were really upset. Then that fall there was a double fatality involving a father and son team (Chris and Chrissie Rouse Jr.) on the unidentified German sub, referred to as the "U-Who" (later identified by John Chatterton and Richie Kohler as the U-869 [Kurson, 2005]). Many feared that these deaths would bring government regulation and effectively shut down technical diving.

Skin Diver magazine went on a rampage with a three-part series in their October, November, and December 1992 issues calling for an end to deep diving and nitrox use or at least a return to the closet. SDM editor Bill Gleason put it this way in his October 1992 editorial titled "Deep diving/nitrox perspective": "Get back in the closet and give responsible divers the opportunity to close and lock the door on deep diving." Gleason, conflating nitrox use with deep diving, showed the lack of information and understanding at the time regarding the technology. Famed *Skin Diver* columnist ER Cross even took a stand with a column titled "Why I won't use nitrox." Meanwhile, the Cayman Water Sports Association issued a warning that the local chambers would not treat divers who had been "bent" while diving nitrox. Of course, at that point it was too late to put the genie back in the bottle.

DEVELOPING COMMUNITY STANDARDS AND BEST PRACTICES

In January 1993, *aquaCORPS* organized the first tech-diving conference, tek93, which was held in Orlando, FL, again just prior to the annual DEMA show. The conference brought together members of the technical, recreational, military, and commercial diving communities for the purposes of education and information sharing as well as addressing the recent spate of diving accidents and what was needed for the technical-diving community to move forward. Out of that first conference came the first set of community consensus standards or "best practices" for technical diving that I worked on with Capt. Billy Deans, owner of Key West Diver, and others; we called it "Blueprint for Survival 2.0," which we published in *aquaCORPS* (Deans and Menduno, 1993).

Essentially, Blueprint was a set of 21 recommendations to improve the safety of technical diving in the areas of training, gas supply, gas mix, decompression, equipment, and operations based on Sheck Exley's original work on accident analysis (Exley, 1979). Exley developed a set of 10 principles or recommendations based on a thorough analysis of cave-diving accidents, which helped reduce cave-diving fatalities. We also kicked off a new section in the magazine called "Incident Reports" that featured detailed analyses of tech-diving accidents, which soon became one of the best-read sections of the magazine.

One of my favorite quotes that we used in the magazine at the time came out of a scientific paper authored by JP Imbert and others (1989), who worked on the Comex's hydrogen-diving program. The quote is: "Safety is the key consideration in diving. It entirely controls depth and time capabilities." Ironically, the paper was titled "Safe deep sea diving using hydrogen."

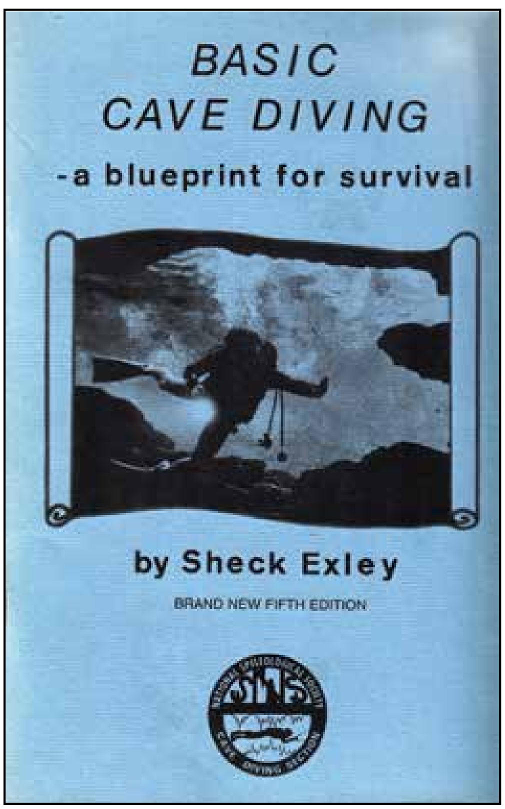


Figure 13. Blueprint original.

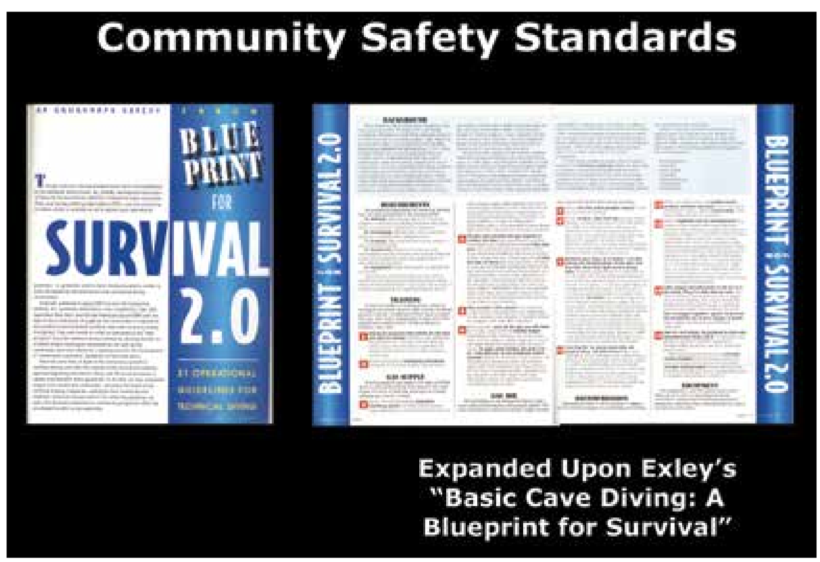


Figure 14. Blueprint 2.0.

Not many people would consider diving to 1,500 ft (457 m) or using hydrogen breathing mixes to be "safe." But that was the lesson we learned back then. Safety is everything!

Over the next few years, based on its improving safety record, technical diving established itself as a legitimate branch of sport diving, and mix technology, in the form of enriched air nitrox, was gradually adopted by the recreational side of the diving business as well. By 1995 PADI along with the British SubAqua Club (BSAC) joined other recreational and technical diving training agencies to offer enriched air nitrox training. The era of single-mix technology (i.e., air diving) was dead.

The result was that mixed-gas technology more than doubled the operational range of self-contained (sport) diving from no-stop dives to 130 ft (40 m), to dives ranging from 15 minutes to several hours at depths up to 250-275 ft (76-84 m). As Deans put it, "We doubled our underwater playground." Though tech divers were conducting a few dives below 300 ft (90 m) at the time, many of us thought that these were exceptional and beyond the reliable range of open-circuit scuba. Most important, technical diving helped fuel the change to what you might call the mixed-gas infrastructure at the retail dive store, which was a necessary step for the eventual emergence of rebreather technology.

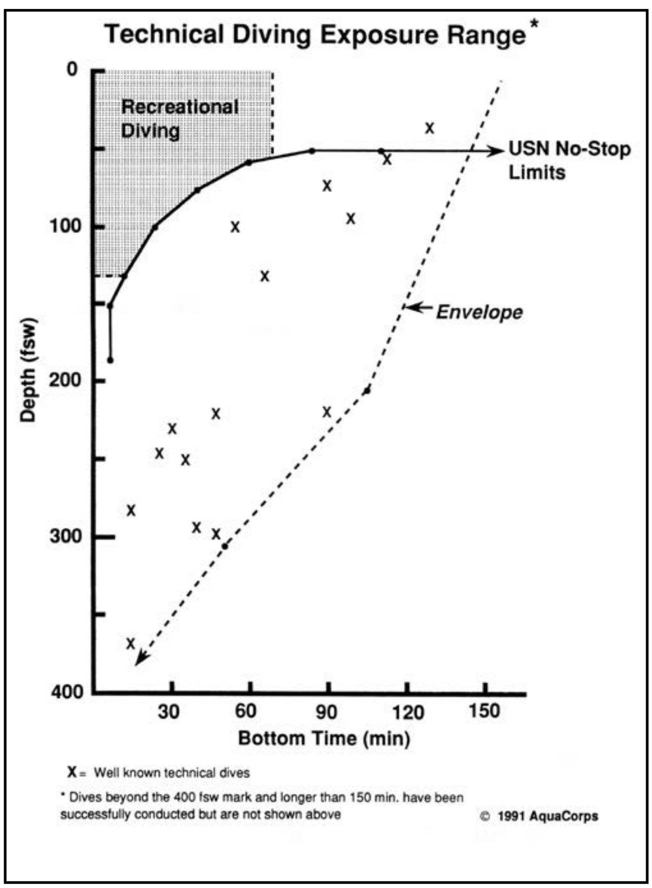


Figure 15. Technical diving range.

BRING ON THE REBREATHERS!

There was a tremendous interest in rebreathers during the early days of tech diving. They were viewed as the ultimate in self-contained diving technology because they could greatly extend bottom times while providing near-optimal decompression in a small package, not to mention their major cool factor. To parrot Poseidon's executive vice president of sales, James Roberton, who said at the Poseidon press briefing at RF3, "You know you want one!" We all did!

There was no doubt in anyone's minds that rebreathers were the future of tech diving and likely self-contained diving as well. Of course, at the time the technology was not readily available.

We began reporting on rebreathers in June 1990 in our second issue of *aquaCORPS,* and we ran one or more articles on the technology in most of the subsequent issues. In January 1993 we devoted an entire issue, the *aquaCORPS* "C2" issue, featuring a *Rolling Stone*-style interview with Bill Stone, interviews with Stuart Clough, Greg Stanton, and Tracy Robinette, articles by many of the early movers and shakers in the rebreather community such as Walter Starck, Bob Cranston, Olivier Isler, Rob Palmer, and John Zumrick, along with a piece on oxygen management by Richard Vann, and even a reprint of a 1969 *Skin Diver* article on Submarine Systems prototype cryogenic rebreather (Kushman, 1969). We also featured several rebreather sessions at the first tek.Conference (tek93) that we held that year in Orlando (Menduno, 1994).

It was clear to many of us that there were many myths and misunderstandings surrounding the use of rebreathers. That was not surprising. No one in the sport-diving community owned a rebreather other than people such as filmmakers Howard Hall and Rob Cranston as well as a few explorers and vendors. So we decided to do something about that. I teamed up with rebreather builder and engineer Tracy Robinette, who had built the ShadowPac in the 1970s (which included the first integrated BOV mouthpiece), and organized the Rebreather Forum, which was held in Key West,

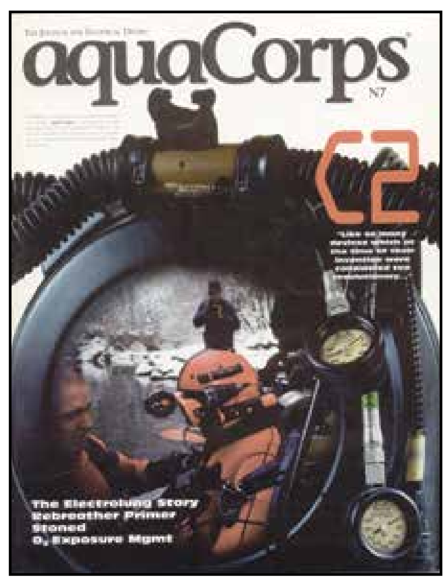


Figure 16. aquaCORPS #7, *"C2," published in January 1993.*

Figure 17. Dr. Ed Thalmann presenting at the aquaCORPS *Rebreather Forum in May 1994 in Key West, FL.*

FL, in May 1994. The forum featured special guests including U.S. Navy diving physiology guru Dr. Ed Thalmann, who oversaw the development of the Navy's mixed-gas decompression tables, and Alan Krasberg, who could arguably be considered the grandfather of mixed-gas closed-circuit rebreathers. It was the first time such a group had been gathered.

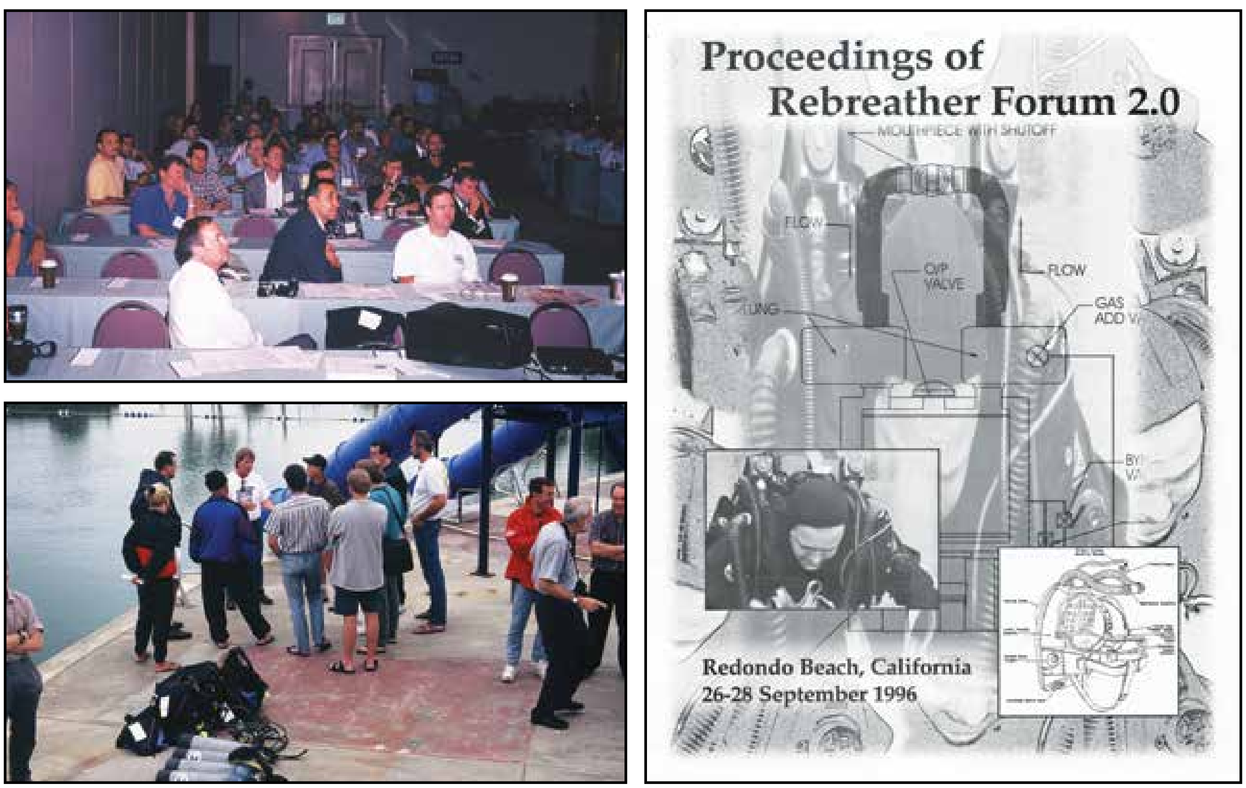
That first forum had 90 attendees including five rebreather manufacturers, numerous training agencies and representatives from the sport, military, and commercial diving communities. As a special treat, we got to tour the U.S. Army Special Forces Underwater Operations School in Key West, which trains divers in the use of oxygen rebreathers. We also had presentations from military trainers from the U.S. and British navies, who taught mixed-gas closed-circuit diving.

The findings from the forum were severalfold. First, there was clearly a market for rebreathers at a $5,000-$10,000 price point. The only problem was that you could not buy one. I remember photographer Marty Snyderman waiving his checkbook in the air challenging any of the manufacturers in the room to sell him a unit. No one would.

Second, the military was the only diving community that was successfully using rebreather technology, and their success was based on strict discipline and massive support, two features likely absent in the sport-diving market. Third, training requirements for rebreather diving were significant. Finally, semiclosed rebreathers were likely to be the first adopted by sport divers because of the relative simplicity and lower cost.

Interestingly, there were few concerns that the technology might not be appropriate for sport divers. To the contrary, it seemed to be only a matter of time. As the prescient PADI technical development director Karl Shreeves observed at the time, "When rebreather technology is ready for the mainstream, PADI will be there to offer training."

We continued to offer rebreather workshops and "try" dives (not "buy" dives) hosted by manufacturers at our annual tek conference. Manufacturers were promising that their units would be available soon, but products were slow to materialize.



Figures 18, 19, 20. Rebreather Forum 2.0.

REBREATHER FORUM 2.0

In 1995 Dräger came out with the Atlantis semiclosed rebreather designed for recreational divers. Having a major manufacturer with more than a half century of rebreather-manufacturing experience enter the sport market gave the notion of sport-diving rebreathers much-needed credibility. In addition, Grand Bleu began selling in Japan a semiclosed unit called the Fieno. Interestingly, though the tech-diving community was booming, it seemed likely that rebreathers were going to be adopted by the recreational community before the tekkies got theirs.

The timing seemed right, so Robinette and I organized RF2, which was held in Redondo Beach, CA, in September 1996. PADI, one of our sponsors, agreed to publish the proceedings of the forum through their Diving Science and Technology (DSAT) subsidiary (Richardson et al., 1996). There were more than 100 attendees along with 15 rebreather manufacturers at RF2. Of those, only five are making rebreathers today.

At the time of RF2, the U.S. and British navies were the largest users of mixed-gas rebreathers, with an installed base of about 240 units in service out of a total of 600 in inventory. There were at most 25-50 units in the tech community. Most of these belonged to small groups such as Stone's team, small boutique manufacturers such as Peter Readey, the principal of Prism Life Support Systems Ltd., a few customers, and a handful of explorers and filmmakers.

With regard to semiclosed rebreathers, Dräger product manager Christian Schultz reported that they had sold about 850 Atlantis semiclosed rebreathers at the time of RF2, and we estimated that there might have been as many as 3,000 Fieno units sold in Japan. Stone's company, Cis-Lunar Labs, had also started selling its MK-IV rebreather that year for $15,000. It would be another year before Ambient Pressure Diving Ltd. launched its Inspiration mixed-gas closed-circuit unit in 1997, and the following year when Jetsam Technologies Ltd. introduced the KISS classic.

There were extensive findings and recommendations resulting from RF2. These are reviewed briefly in light of what we know today in an appendix to this paper; each finding is assessed as to whether progress has been made and if not, why not.

At the time of RF2, safety was viewed as the biggest challenge in adopting rebreathers for sport diving. In the words of Deans, "The challenge is going to be bringing the technology to market without killing too many divers in the process!" That same year, *aquaCORPS* ran out of funding, and I was forced to shut down the company. Needless to say, it was a sad year for me.

ON TO THE "REC" REVOLUTION

Today, according to industry experts, there are an estimated 10,000-15,000 active rebreather divers in the sport-diving community and likely at least as many units (Menduno, 2012). There are also more than a dozen manufacturers; the majority were not in existence at the time of RF2, and most of the leading brands have CE certification (European marking of conformity). The market for semiclosed rebreathers, which was once thought would dominate sport diving, has proved to be limited, though several vendors are introducing new semiclosed systems designed for recreational divers. Needless to say, rebreather technology has greatly expanded our underwater envelope.

I spoke with many manufacturers prior to RF3, at which point the enthusiasm was high. Manufacturers were excited about the technology, and it seemed that each company had focused on a particular aspect of rebreather technology, which they have incorporated in their units. Overall, it seemed like a very vibrant market with a lot of innovation since its emergence more than a decade earlier. Some of these innovations included the advent of digital controllers, integrated computation, digital HUDs, active-validating O_2 sensors, CO_2 sensors, vibrating and audio alarms, increased automation, integrated BOVs and more. The supply side of the market was clearly evolving.

So are the buyers. Back in the 1990s there were clearly distinguishable recreational divers and technical divers but not much in between. But over the past decade a middle market of sport divers has grown. There are still recreational tourist divers and high-end explorers. But now there is a bigger market in between — call them tec-rec divers or experienced sport divers — who are buying rebreathers. As Mike Fowler, CEO of Silent Diving LLC, which distributes Ambient Pressure Diving rebreathers in North America, explained to me, "Sport divers, as distinct from technical or open-water divers, are the largest part of our market."

So it is clear that the market has evolved. It is what Mark Caney, PADI vice president of rebreather technologies, elegantly explains as a technological tripod. According to Caney,

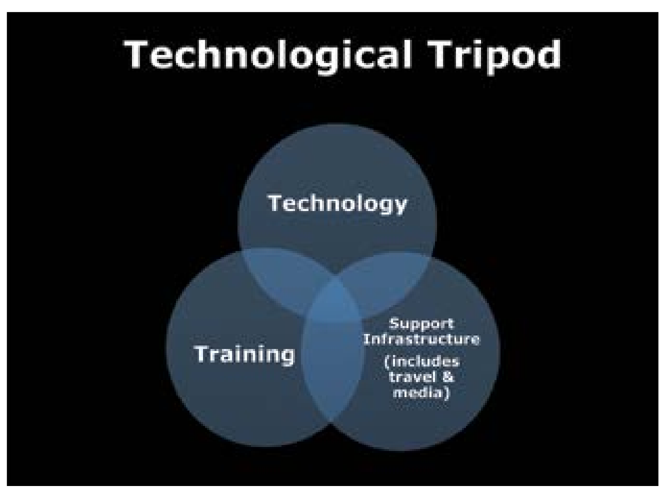


Figure 21. Technological tripod.

there are three components necessary for a diving technology such as nitrox, or in this case rebreathers, to scale up for the mass market: The technology must be robust and reliable, you need adequate training to be in place, and you need the infrastructure to support it both at a local retail level and at dive destinations.

Many people I spoke to feel that this evolution has taken us to a new inflection point, which is perhaps best symbolized by the Poseidon MK-VI, designed for recreational divers, and the new PADI recreational rebreather program. Call it the "consumerization of CCR." As Hammerhead manufacturer Kevin Jurgensen, principal at Jurgensen Marine Inc., put it, "At Rebreather Forum 2.0 we were in the American Telephone & Telegraph stage. Now we are in the Motorola/Nokia handset stage, and Stone is trying to build an iPhone."

Interestingly, a similar phenomenon is now going on in the computing world, where consumers are now beginning to drive enterprise information technology departments. This is the final cycle in the technology paradigm that I spoke of earlier. Consumers (divers) are beginning to drive the market for rebreather technology with what Caney and the people at PADI have defined as TYPE R (recreational) rebreathers.

Figure 22. Call it a "rec" revolution.

As you have probably seen, PADI advertises this evolution as a "Tec Revolution," but it is really a "Rec Revolution." PADI offers a technical rebreather program to be sure, but the real innovation is their recreational rebreather program, which is based on simplified and highly automated TYPE R rebreathers used in a limited case of no-stop dives to 130 ft (40 m) or less.

This move to bring rebreathers to the recreational community is not without controversy. On the one hand, some industry veterans are behind making the technology available to recreational divers. Joe Dituri, vice president of IANTD, explained it this way: "You are too old if you think rebreathers will not work for recreational divers. Kids are smarter on electronics than we ever were, and they are goal oriented. I say get on board now or be left at the gate."

On the other end of the spectrum, Jarrod Jablonkski, founder and CEO of Global Underwater Explorers (GUE), said, "Really? This is what this has come to as an industry? We are going to push this technology on a group of people who are wholly unprepared to manage a rebreather, and we are going to promote it because we can make money doing it."

Many people are legitimately concerned that bringing this technology to the recreational market could end up hurting people if they are not prepared for it. As Jurgensen said, "We know that complacency kills. What I worry about is that recreational divers have complacency times a hundred."

THE ELEPHANT IN THE LOOP

Arguably one of the most pressing issues surrounding rebreathers is their safety record. Dr. Andrew Fock, the head of hyperbaric medicine at the Albert Hospital in Melbourne, Australia, presented a sobering talk at Oztek last year about rebreather fatalities, "Killing them softly," derived from a recent paper (Fock, 2013). He presented again at RF3. I will touch on a few of his salient points here.

Between 1998 and 2000, 181 diving fatalities with rebreathers were reported, averaging about 10 per year prior to 2005 and approximately 20 per year since. It appears that 20 or more divers have died since 2010, bringing the total number of deaths to more than 200. Many of the deceased were diving's best and brightest, and the toll on the community, particularly for those who lost friends, has been particularly heavy. No one has counted the near misses.

To put these numbers in perspective, there was a combined total of about 100-120 sport-diving fatalities per year on average in the U.S., Canada, U.K. and Europe over the same period, which probably represents a large percentage of the worldwide sport-diving market. (No one keeps worldwide diving fatality statistics.) Based on these numbers, rebreather fatalities represent about 15 percent of the total each year. But now consider that there are as many as 1.2 million active scuba divers in the U.S. alone according to a 2007 analysis by *Undercurrent* (again there are no confirmed numbers), but likely there are no more than 10,000-15,000 rebreather divers worldwide.

This would suggest that the fatality rate for rebreather diving is significantly higher than its open-circuit counterpart. In fact, based on incident data from Divers Alert Network (DAN), DAN Asia-Pacific, BSAC, Deep Life, and Rebreather World databases, Dr. Fock estimated that the rebreather fatality rate is likely about 5-10 times greater than for open-circuit scuba, or about 4-5 deaths per 100,000 dives. Furthermore, he found there was no difference in fatality rates among manual or electronic units or specific brands of rebreathers; accidents were roughly proportional to market share. Fock also noted that while the data suggest that deeper dives carry greater risks, a large number of rebreather fatalities occur in shallow depths within the recreational envelope.

It should be considered that, historically, fatality rates are often disproportionately high in the early phases of many "civilian" adventure sports such as flying small aircraft or hang-gliding until participants are able to create suitable safety paradigms. Early technical diving is a case in point. However, it has been a little more than 15 years since the first production of closed-circuit rebreathers were introduced to technical divers, and the accident rate still appears to be quite high. Many people think this begs the question: If the technical-diving community has been unable to get it together, how much better will the recreational-diving community fare?

In fact, it is probably a blessing that rebreathers are still two to three times the cost of open-circuit equipment. If there were $2,500 closed-circuit rebreathers on the market right now, there would likely be a lot more units sold and perhaps more dead divers. Clearly, diver safety is a key issue that must be addressed if the technology is to scale to a larger audience of users.

OVERCOMING DIVER ERROR

I spoke to several dozen manufacturers, engineers, instructors, hyperbaric physicians, attorneys and explorers in the months prior to RF3 about the fundamental causes of rebreather fatalities and what needed to be done. Though I found differing opinions about the remedies, there was an overwhelming consensus of views as to causation.

In a nutshell, though some problems can probably be best addressed by human factors such as engineering, the fundamental problem appears to be operational — i.e., the inability of divers to properly maintain and operate their rebreathers and not necessarily a failing of the machines themselves. It is a problem of "human error" or, as Fock puts it, problems with the human-machine interface. These manifest in a variety of ways: failure to use checklists, complacency, carrying insufficient bailout, conducting risky behaviors such as solo diving, pushing too far beyond one's limits, extreme exposures, etc. In addition, rebreather demographics favor older individuals who can afford the technology but may not be in as good of shape as they once were. This group may be more prone to heart attacks and other health problems that have an impact on the statistics. The problem, most agree, is likely one of both training and culture.

"I have yet to do a forensic examination of a fatal accident and see where a unit failed. It is always diver error," Technical Diving International (TDI) founder Bret Gilliam explained to me in an interview. Gilliam has worked as an expert witness for more than two decades. "Divers are killing themselves because they made mistakes in their maintenance and predive checks or during the dive," he said. "Unfortunately, rebreathers require diligence to detail and are not very forgiving. If you, the operator, make a mistake, there is very little room for error, and most divers do not recover. And that points directly to training and experience."

Though most of the people I spoke with agreed that rebreather training has improved over the last decade and good training is available, many felt that more consistency is needed. "Some of the training has become a little too personal," explorer, educator and filmmaker Jill Heinerth told me. "Everyone runs their own courses. That may be OK for someone like me with lots of experience, but what about the new instructor?" Some of the instructors also noted that the quality of training materials varies widely, and some of it is of poor quality.

Interestingly, many people feel that PADI's entry into the rebreather training market will help raise the bar. "PADI will help create some of the consistency that has been lacking," said Fowler, who is an active instructor in addition to running Silent Diving. "Students are likely to get a reasonably good class even if the instructor is weak." Not surprisingly, their rebreather training materials generally receive high marks from those who have reviewed them.

However, there is still some tension between the training agencies and the Rebreather Education and Safety Association (RESA), which was formed in 2010 by the manufacturers. As the CEO of a rebreather manufacturer told me, "All manufacturers have problems with instructors. That is one reason we created RESA, because the agencies are out of control." Conversely, the agencies say that the manufacturers are not letting them do their job. As a training agency executive put it, "I tell the manufacturers, 'Get out of the way, and let us do our job. Ours is to teach. Yours is to build good rebreathers!'"

At issue is to what extent manufacturers should set training standards for the agencies versus letting the agencies set the standards. Manufacturers do not set training standards in the case of open-circuit scuba diving. For example, RESA recently mandated that all rebreather training needs to be conducted in "stock" (unmodified) rebreathers, though many and possibly most individuals end up modifying their rigs to some extent. This is currently a hotly debated subject among instructors. Another more fundamental issue is whether training agencies that join RESA should be allowed to vote. Currently they are not. It is hoped the tension will lessen as RESA and the training agencies work through these and other issues.

Others expressed concern about the challenge of growing the pool of instructor trainers and instructors to serve a wider audience of divers while maintaining quality. "We will have a problem as an industry if we allow the quality of instructors to dilute in order to build numbers," warned tech veteran and educator Steve Lewis. "The instructors who fast-tracked their experience are the ones who are not prepared when Murphy comes calling."

DEALING WITH A NON-COMPLIANT SPECIES

Though some issues can be addressed by training, insiders say improving rebreather-diving safety may come down to changing diving culture—what happens after training. Currently, one of the biggest safety issues surrounding rebreathers is the fact that divers become complacent and do not rigorously adhere to a predive checklist in assembling and preparing their unit for diving as they (presumably) learned in class and also neglect required postdive maintenance. Even worse, some divers choose to dive knowing that there are problems with their unit such as a faulty sensor or small leaks.

Finding solutions is easier said than done.

"We are a non-compliant species," lamented Heinerth when I spoke to her. "How do you change that?" Heinerth, who has affectionately been referred to as the "Checklist Mistress" by colleagues, said that training is partly responsible, but the issue is more a matter of culture. "I know that some of my students have stopped doing their checklist. But I do not know the cure. We have to police each other. If we do not, we are liable to wind up with minefield of dead divers and more lawsuits, and it will only be a matter of time before land-owners and boat captains will no longer allow rebreathers."

How do we as a community encourage divers to do checklists and support their adoption within the culture? "We need to get to a place where it is cool to do checklists and people are not afraid to say to a buddy, 'Do not get in the water with only two of three sensors working,'" emphasized Bruce Partridge, founder and CEO of Shearwater Electronics and a member of RESA, in our interview. "I really believe it is a community problem. If you are flying an aircraft, we can make a rule. If your equipment is not working properly, you cannot fly. But unfortunately we cannot do that with divers."

The problem is compounded by the fact that there is no adequate community reporting system in place, or rather there is a broken reporting system at the present time. As Partridge put it, "How do you improve diver safety if no one will tell you what caused the fatalities?"

This is clearly an important issue. The result is a lack of data regarding what went wrong. Part of the problem is due to the fear of litigation, the high costs of discovery, commercial interests that do not want information released, and broken community trust. And if a lawsuit is filed, everything gets closeted in confidentiality agreements unless a trial verdict is brought forward in the public record. There is also a lack of non-fatality reporting, the "I learned from that" type of forums. Of course, these days no one wants to admit to a mistake much less post it online given today's divisive "got-ya" online culture.

There were a number of people at RF3 who have been looking into the problems of establishing a community reporting system including Andrew Fock, Garrett Locke, Bruce Partridge, Neal Pollock, Richard Pyle, Dick Vann, and others at DAN. Unfortunately, little time was spent at the forum discussing the issue of reporting.

Though manufacturers and researchers need this information, so do divers if they are going to take a proactive role in improving rebreather diving safety. As we learned from the early days of tech diving, accident reporting is a critical community resource.

Some of the people I spoke with think that the community might benefit from an industry-backed accident investigation team much like what the Federal Aviation Administration (FAA) uses to get accurate and detailed accident information. I have heard so many people ask, "What actually happened to Wes Skiles?" (Skiles, a veteran underwater filmmaker, died during a film shoot in July 2010 while diving a rebreather.) "I wish we knew." Exactly. We do not. So industry investigation teams might be very useful but also likely to be difficult to implement due to politics and other issues.

ENGINEERING IMPROVED SAFETY

Many insiders believe that the other opportunity for improving rebreather safety is through engineering. There are three main aspects to this. First, improved automation can make the human-machine interface more manageable. This is the thrust of Caney's ideas to create a TYPE R rebreather exemplified by the Poseidon MK-VI, and more recently the Hollis Explorer, which were designed specifically for recreational divers. Second, improvements are needed in oxygen sensing, and third, improvements are needed in sensing CO_2, which has been called the "dark matter" of rebreather diving.

Technical-diving educator Joel Silverstein, president of Technical Diving Limited, put it this way: "Compare a rebreather to your car," he said. "You do not have to reach behind your seat and turn on the fuel pump or make sure that the brakes are on or interpret four flashes, three beeps and two dashes to see if the unit is working." Like automobiles, improved electronic automation seems to be the best way to make the human-machine interface more manageable. There are some people that feel electronics are not reliable and should not be relied on. But I think the better question is, are they more reliable than our fallible brains?

Of course, there are groups such as the "do it right" (DIR) community and others that are suspicious of dive computers, let alone electronic rebreathers, and some of these people have opted for manually operated rebreathers without an electronic solenoid. But most of the people I spoke with do not see this as the way to the future. Rather, they think the future lies in automating out the possibilities of diver error to the extent possible.

Dr. Bill Stone and his team, with others such as diving engineer Kevin Gurr, founder and CEO of VR Technology Ltd., who designed the Sentinel and the Hollis Explorer, are working on the problems of automation. Stone said, "The real frontier is automating these devices from their current 'test pilot' stage to enable divers to go back to what is really at stake here: enabling divers to have fun being in an alien environment." Jurgensen mentioned the "iPhone" as a metaphor for some of this automation work; and, in fact, that is the way that technology and society are moving.

Based on my interviews, the other areas that need work are O_2 and CO_2 sensing technology. I am sure that there will come a time 10 years or so from now that we will look back on today's "test-pilot-era" technology (in Stone's words) and regard it as primitive. "You actually dived those units without knowing exactly what you were breathing? OMG!" It will be like us looking back at early cave divers using J-values (reserve) and empty Clorox bottles for buoyancy, and saying, "Really?" I say 10 years as opposed to one or two because rebreather technology is evolving much more slowly than computer technology. That is because the volume of units (and therefore the money that manufacturers have available for innovation) is infinitesimal compared with smartphones and tablets.

Most experts seem to agree that the current oxygen-sensing systems are the weakest component of today's rebreather and also the most critical. Dr. Arne Sieber, CEO of Seabear Diving Technology, who came out of the biomedical industry, and Nigel Jones, principal at RMB Consulting who works with Stone Aerospace, offered a new approach to oxygen sensing. Both Sieber and Stone Aerospace have developed "active validation systems" such as what is used in the Poseidon MK-VI, which calibrates and tests the validity of the oxygen sensors (the MK-VI uses two sensors) throughout the dive using onboard diluent and oxygen. These systems arguably represent an innovation from the 50-year-old voting logic systems that were developed in the early 1960s to address the use of unreliable galvanic oxygen sensors, though not all manufacturers believe they are necessary.

The need for CO_2 sensing is well established, and it has been a long time in coming. There are several issues here. First, there is the need to monitor scrubber consumption/duration in real time. Second, it is critical to be able to detect if there is a CO_2 breakthrough arising from a spent canister, channeling, or a mechanical failure of some type. Ambient Pressure Diving and others have reported that they have had good results with their thermal sensor, or "Temp Stik," which was developed in parallel at Ambient Pressure and the Navy Experimental Diving Unit (NEDU) to measure canister duration. Gurr, at VR Technology Ltd., has adapted the technology to his Sentinel rebreather and has also pioneered a gaseous CO_2 sensor that can be used to detect breakthrough as described in these proceedings. Many of those who I interviewed thought that divers often push their scrubbers beyond the limited manufacturer test data.

DO OPERATIONAL STANDARDS OFFER A SOLUTION FOR IMPROVING SAFETY?

I have discussed changing diving culture to improve rebreather safety, for example, by making it "cool" to do checklists or sit out a dive in the case of problems with a unit, and also improving safety through better engineering. However, one question that has not been asked is whether a standards-based approach to rebreather diving might play a role in reducing the number of fatalities in the sport-diving community. By standards I mean operational or diving standards (i.e., specific equipment configurations and procedures that divers agree to adhere to when conducting dives as opposed to training standards promulgated by dive training agencies, which dictate how a diving instructor conducts a class).

Outside of the sport-diving community, which began using rebreathers in the mid- to late-1990s, military divers have been the only community to successfully use mixed-gas rebreathers for diving operations. According to representatives at RF2, the military's success in managing the risks of rebreathers is due to their high degree of discipline and training, extensive supporting infrastructure and reliance on a standards-based approach to diving.

To quote from the RF2 proceedings, "The military objective is to eliminate human error and exercise a degree of control over rebreather usage through written procedures, testing and certifying units before they are released to the fleet, mandatory predive and postdive checklists, adherence to the buddy system, reliance on dive supervisors, and tracking problems in the field." It should be noted that military standards also require the use of full-face masks or mouthpiece straps when using a rebreather to protect the diver's airway in the event of unconsciousness. Of course, the reason to eliminate human error and or have systems to catch errors when they occur is that this appears to be the cause of most rebreather fatalities as discussed earlier.

Though standards-based diving is commonplace in the commercial-, military- and even scientific-diving communities, it is rare in sport-diving circles given the laissez-faire nature of the activity. Many sport divers likely view standards as an infringement on their independence. Though a standards-based approach has not been adopted by and large by open-circuit technical divers (though there are many recognized best or common practices), rebreathers are far more complex than open-circuit scuba and are more subject to diver error and consequently might benefit from a standards approach.

My personal experience is that there is a wide range of configurations, practices, protocols and knowledge among divers, much moreso than with open-circuit tech diving. In fact, almost every rebreather diver I have dived with has a different approach. How would standards such as common equipment configuration, standard gases, and team diving help? By simplifying operations, making it easier for team members to catch errors and problems before they get out of hand, and by making sure that everyone is on the same page. Accordingly, I offer a couple of examples for consideration drawn from the sport-diving community that suggest what a standards-based approach to rebreather diving might look like and how it might help improve rebreather safety.

The first example comes from the early cave-diving community. In the 1970s cave divers faced diving-safety issues, not unlike rebreather diving today, when an increasing number of fatalities threatened the viability of the sport. In response, the community created a "safety culture" built around a set of 10 recommendations or "best practices," such as running a single continuous guideline from the entrance of the cave throughout the dive and using the "rule of thirds" for gas management. As discussed earlier, Exley (1979) developed these recommendations using accident analysis. And though they were voluntary, they became common practice — who would want to dive with someone who consistently violated the thirds rule? As a result of instituting these practices into cave training and culture over the ensuing years, the number of cave-diving fatalities fell dramatically.

Early tech divers took a similar approach with "Blueprint for Survival 2.0" a decade later (Deans and Menduno, 1993). Though a set of standards were never formerly adopted, best practices such as carrying a long hose, keeping oxygen levels at a PO_2 of 1.4 atm or less during the working portion of a dive, properly analyzing and marking the content of cylinders, reliance on team diving where possible, and the use of support divers (at least on expeditions) became common practices, and the number of incidents fell.

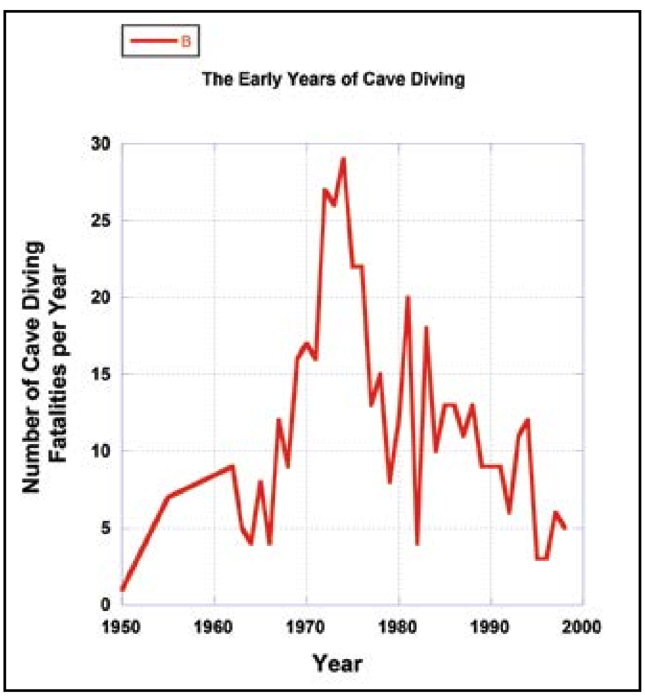
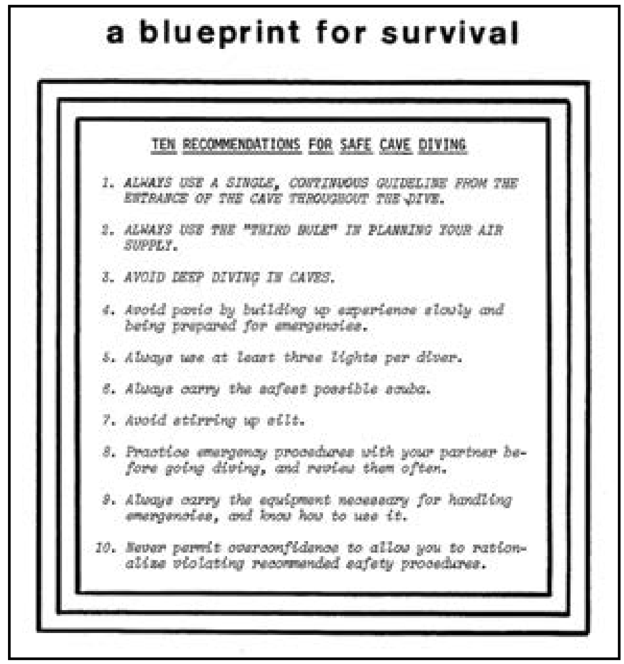


Figure 23. Cave-diving fatalities.

Recently, there has been some discussion among some rebreather veterans that a similar set of voluntary "best practices" for rebreather diving, call it "Blueprint for Survival 3.0," should be created and promulgated. Codifying a set of "best practices" for rebreather diving is the first step toward creating a standards-based model. However, to date no one has compiled a Blueprint 3.0.



a blueprint for survival

TEN RECOMMENDATIONS FOR SAFE CAVE DIVING

1. ALWAYS USE A SINGLE, CONTINUOUS GUIDELINE FROM THE ENTRANCE OF THE CAVE THROUGHOUT THE DIVE.
2. ALWAYS USE THE "THIRD RULE" IN PLANNING YOUR AIR SUPPLY.
3. AVOID DEEP DIVING IN CAVES.
4. Avoid panic by building up experience slowly and being prepared for emergencies.
5. Always use at least three lights per diver.
6. Always carry the safest possible scuba.
7. Avoid stirring up silt.
8. Practice emergency procedures with your partner before going diving, and review them often.
9. Always carry the equipment necessary for handling emergencies, and know how to use it.
10. Never permit overconfidence to allow you to rationalize violating recommended safety procedures.

Figure 24. "Blueprint for Survival" best practices for cave diving.

A second example for consideration is GUE, a nonprofit, membership-based exploration and conservation organization founded in 1998 by explorer/educator Jarrod Jablonski and hydrologist Todd Kincaid. The organization is a hybrid training agency, dive club with local affiliates and a conservation group like the Sierra Club, which has grown to several thousand members worldwide. As such they are a unique organization, though in some respects they are similar to BSAC.

GUE is somewhat controversial in sport-diving circles because it does take a standards-based approach to diving similar to commercial or military diving. As a result, some people jokingly refer to GUE as the "dark side" and compare them to Scientologists or *Star Trek*'s Borg, because for the most part they all wear the same gear, configured in a specific manner, often in the same colors, and they all follow the same protocols. And they are not alone. Other spinoff groups such as Unified Team Diving (UTD) and other DIR groups also rely on standards-based diving.

Ironically, GUE's adherence to standards has enabled their divers to conduct very aggressive expedition-level diving around the world with an enviable safety record. Jablonski told me that the organization has had only a single fatality during training and GUE-sanctioned dives since its inception in 1998.

It should be noted that GUE does not currently sanction or support the use of closed-circuit rebreathers, but GUE launched a "pilot" CCR program in late 2013. Their standards have been developed for open-circuit scuba diving. GUE does have a limited program of using a non-electronic, semiclosed "gas-extender" system called the Halcyon RB-80 for special applications; however, these units are in very limited use by the small number of explorer-level members who have completed all of GUE's technical training. Nevertheless, GUE offers a number of ideas that arguably could improve rebreather diving safety.

Figure 25. GUE divers ready to splash.

First, GUE divers rely on a standardized equipment configuration for their open-circuit diving rigs — for example, placing and deploying the long hose on one's primary regulator, positioning and using one's primary canister light for communications, and weighting one's rig to facilitate good horizontal trim. They have also standardized what breathing mixtures to use at various depths, which simplifies dive operations. For example, GUE uses nitrox 32 (32 percent O_2) for dives to 100 ft (30 m) — they do not dive air, which is viewed as a suboptimal breathing gas. Helium mixes are used beyond 100 ft (30 m) to minimize narcosis and the work of breathing.

GUE divers also rely on team diving, where your buddy is never any more than a kick or two away. Solo diving is not sanctioned. The team performs a standardized predive checklist on every dive, and there is also a specific team protocol for gas switches, decompression and deploying a surface marker buoy.

GUE divers plan for adversity; it is one of the organization's central tenets. Accordingly, GUE encourages divers to regularly practice safety skills such as valve shut-off drills or sharing gas during a simulated out-of-air drill, which are also a core element of GUE training. Instructors also routinely simulate unplanned emergencies such as an out-of-air emergency, leaky valve or loss of a face mask during training classes and require that students respond accordingly.

Finally, local GUE affiliate groups, such as the Bay Area Underwater Explorers (BAUE) or San Diego Underwater Explorers (SDUE), sponsor frequent projects and events, which are a great excuse to do a lot of diving together and provide needed mentoring, which is important in diving, as well as having fun. To participate in group dives, members agree to follow the GUE standards. They also are allowed to conduct dives only at their training level on membership dives. (Outside of membership dives they can do what they want, of course.) I believe that the BSAC follows a similar approach with respect to club dives.

Similar to military diving, GUE practitioners say that their standards-based approach helps prevent diving accidents. Applying this same approach to rebreathers — i.e., using standard rebreather configurations and gases, mandatory checklists, team diving and staying within one's training limits — could reduce diver error and therefore improve rebreather diver safety. GUE is currently in the process of developing a standards-based closed-circuit program, which will likely be released in the next few years.

That leads me to my final example, the Association of Rebreather Training (ART), founded by explorer and educator Mathew Partridge in 2005, which provides factory training for the JJ-CCR, Sentinel/ Ouroboros, Megalodon, and Inspiration/Evolution using a workshop-based approach. More than just a rebreather-training agency, ART has developed a set of operational diving standards for rebreathers akin to GUE's standards for open-circuit diving. The standards include specifications for rebreather configuration, diluent and bailout selection, checklists, and emergency protocols. ART also adheres to team diving. To date, ART has trained several hundred rebreather divers and conducted numerous workshops. Though the organization is still in its infancy, the work that Partridge has done shows promise for improving rebreather diving safety. UTD also has a standards-based rebreather diving program.

Some people may argue that having operational diving standards similar to those described above creates rigidity and that having standards makes it difficult to incorporate new information — for example, improvements to procedures on the basis of accident analysis. Though this is potentially one of the drawbacks of having standards, how can improvements based on new information be effectively disseminated and implemented when individual divers are left to their own devices to do whatever they believe is best? Another problem is that standards-based diving is likely not applicable to all sport divers, the majority of which do not belong to a membership organization such as ART, GUE, or BSAC.

Nevertheless, standards-based rebreather groups may help to inform and raise the bar for others in the sport-diving community to follow as they have to some degree with open-circuit technical diving. It is possible that organizations such as BSAC and other training agencies may eventually take a similar approach in creating their own set of operational rebreather standards to be used after the class is over. Individuals may also form local user groups or rebreather clubs that agree to adhere to a set of rebreather diving standards. Historically, standards-based diving has proven to be an effective way to improve diving safety in a variety of communities.

Ultimately, if we can catch diver error and consequently decrease rebreather incidents to a level close to that open-circuit scuba, particularly as the technology becomes available to a broader set of users, then we can more readily venture out into the underwater environment, and as Exley suggested, "Go see what's there."

APPENDIX. Assessing Progress on Rebreather Forum 2.0 Findings and Recommendations

The numbered, bolded conclusions are reprinted from the Proceedings of Rebreather Forum 2.0 (1996), followed by a brief discussion of the progress made to date.

1. There are many outstanding issues that must be addressed if rebreather technology is to safely and reliably be incorporated into nonprofessional diving applications.

Both the technology and the sport-diving community have come a long way since RF2. Today there are an estimated 10,000-15,000 active rebreather divers in the sport-diving community and likely about that many units in service. This represents a tenfold increase from the mid-1990s, when the military was the largest user group. Similarly, the technology has seen significant improvements, including reliability, the advent of digital electronics, HUDs, BOVs, integrated dive computers, new oxygen control methods, CO_2 sensors, and audio and vibrating alarms. To be sure, there are still outstanding issues to be addressed, such as improving diver safety, making training more consistent, creating better reporting systems, and improving the technology, particularly as rebreathers are now being marketed to recreational divers as distinct from technical divers. But the issues are subtler and based more on community and user experience than in 1996. Many of these issues were addressed at RF3.

2. Rebreathers are far more complex than open-circuit scuba equipment due to their design and function.

3. Because of their complexity, rebreathers have a number of insidious risks not found in open-circuit scuba.

The risks of rebreather diving are now well known and documented in training materials and elsewhere, and it's fair to say that there is a much higher degree of community awareness of the unique risks compared with open-circuit scuba, which was not the case in 1996.

4. The military have been successful in managing the risks through the use of a large supporting infrastructure, a high degree of discipline and training. Comparable infrastructure, discipline and training have not been needed in sport diving until now and currently don't exist in the market.

In the nearly decade and a half since RF2, the technical-diving community has acquired a significant body of experience with rebreathers and have surpassed both the depth and duration range of military rebreather diving. However, the safety record for rebreathers is still a matter of concern. To date, there have been more than 200 recorded sport-diving fatalities involving rebreathers from 1998 to the present; according to experts who have reviewed the data, the overwhelming majority were due to diver error. Arguably, many, if not the majority, of these incidents might have been prevented with better discipline and support infrastructure including checklists, team diving, adequate bailout, etc. My sense is that the majority of the rebreather community would say that better operational support and training is needed if we are to improve rebreather safety.

5. Manufacturers and training agencies must provide appropriate warnings and documentation to the risks of rebreather diving, with an emphasis on those that differ from open-circuit scuba.

Manufacturers and agencies are providing warnings and documentation as discussed above.

6. Some attendees stated that the relative simplicity and low cost of constant-mass-flow semiclosed systems, which have no electronics, may make them more suitable for recreational divers.

7. Despite their relative simplicity, mass-flow semiclosed systems can be problematic. A major concern is dilution hypoxia. A secondary concern is decompression illness.

8. Military semiclosed units are designed to handle workloads as high as 3.0 liters per minute oxygen consumption. However, at this time there are no similar specifications for consumer rebreathers, and some systems may not handle an oxygen requirement this high.

As discussed above, Dräger introduced their Atlantis semiclosed unit rebreather designed for recreational divers the year prior to the forum and had sold approximately 850 units worldwide. Grand Bleu had also introduced the Fieno-S in Japan and had announced plans to bring the unit to the U.S. market. So at the time of the forum it seemed that semiclosed units would be the first rebreathers to hit the sport-diving community.

However, Dräger stopped producing the Atlantis and subsequent semiclosed models in 1999. According to sources, the comparable performance of the semiclosed units versus open-circuit scuba did not justify the price, and sales lagged. In addition, the company, which did not have experience selling to consumers, also suffered distribution problems. Meanwhile, Grand Bleu went out of business and never exported its Fieno unit outside of Japan. By that time, sales of closed-circuit units such as Ambient Pressure Diving's Inspiration and Jetsam Technologies Ltd's KISS began to take off, and the manufacturers turned their attention to closed-circuit technology.

The one exception was a semiclosed unit called the Odyssey, originally developed by Jack Kellon of RBC Inc. Kellon sold the technology to Brownie's Third Lung, and it was eventually acquired by Halcyon Dive Systems, which created the RB80 semiclosed rebreather used by the Woodville Karst Plain Project (WKPP) in their exploration of Wakulla Springs. Halcyon still manufacturers the RB80, and its sister organization, GUE, offers training on the unit, although it is limited to GUE's most experienced divers. Today, they are the only sport-diving group using semiclosed rebreathers. However, that is about to change.

Jetsam Technologies Ltd. has introduced the KISS GEM semiclosed rebreather. To address possible hypoxia problems, the manufacturers warn divers to breathe open-circuit scuba or breathe the unit in open-circuit mode and not breathe the loop at the surface or within 20 feet (6 m) of the surface. In addition, Hollis Inc. and VR Technology are set to launch a hybrid, electronic semiclosed nitrox unit called the Explorer in the coming year. The unit is designed for recreational divers and will reportedly offer performance closer to that of a closed-circuit unit. It remains to be seen how much traction these units will have with recreational divers compared with closed-circuit units.

9. Compared with open-circuit scuba, rebreathers require significant ongoing maintenance and support to function properly. Manufacturers must provide written procedures, predive and postdive checklists, and a schedule for required maintenance.

RF2 acknowledged the efficacy of using diver checklists for improving diver safety. Checklists are a standard tool in military diving as well as in other fields such as medicine and flying that share technical complexity. However, in surveying the community, it is clear that the use of checklists is not the standard, and many divers stop using them after logging their first 50 or so hours. In addition, many manufacturers have not provided specific build, predive and postdive checklists.

RF3 added two findings specifically on the use of checklists, which were identified as the single most important action to improve diver safety. The new findings charged manufacturers with producing carefully crafted predive and postdive checklists for their units. Similarly, agencies and instructors were charged with taking a leadership role in promoting their use. As cave explorer, educator, and filmmaker Jill Heinerth exhorted, "Industry leaders need to be role models. We need to make it cool to do checklists!"

10. Supporting rebreathers on a retail level will likely involve far more work and expense than with open-circuit scuba equipment. Proper oxygen cleaning and handling procedures will need to be used.

Mixed-gas infrastructure, including the ability to pump enriched air nitrox, trimix, oxygen, and argon, is now widely available in most major diving areas as a result of the technical diving revolution. However, very few dive stores are set up and/or have the expertise to sell, service and support closed-circuit rebreathers. Today, most manufacturers sell and service their units directly, though several companies catering to recreational divers — Poseidon, Ambient Pressure Diving, and Hollis Gear — are building a dealer/dive-shop network. Many people in the community believe that having a local dealer network is necessary for rebreather technology to scale for widespread usage.

11. Consumer rebreather training is in its infancy and is not yet standardized.

12. Taking a manufacturer-approved rebreather course is only the first step. Rebreather diving must be learned by experience and sometimes may require many more hours than open-circuit scuba to attain comparable competence as a result of its complexity.

13. Ideally, rebreather instructors should own or have on-demand access to the rebreather that they plan to train other divers on. It is recommended that they have the necessary experience for competence before qualifying as instructors, which may be more than 100 hours with some models and types.

14. Because many aspects of training are specific to individual models, manufacturers need to work closely with training organizations that are developing instructional courses. Manufacturers need to include documentation and manuals with their units.

Rebreather training has come a long way since the mid-1990s, when there was no standardized training and open-circuit instructors were able to attain their CCR instructor ticket even if they didn't own a rebreather. At the forum, three of the oldest technical training agencies — ANDI, IANTD, and TDI — reported that they collectively issued more than 30,000 rebreather certifications from the early to mid-1990s through 2011. These likely represent the largest share of agency certifications. About 18,000 of these were basic certifications, and approximately 12,000 were intermediate and advanced certifications. Not included in these numbers are certifications from PSA International, BSAC, and the Rebreather Association of International Divers (RAID). However, at the present time there is not a consistent set of publically available minimal training standards recognized by all agencies. This was one of the findings of RF3.

Today, rebreather instructors are expected to own, have access to and have time on the units that they use for teaching. In addition, in 2010 rebreather manufacturers banded together to form the Rebreather Education and Safety Association (RESA) to work with training agencies and others to ensure the quality of both courses and instructors. Many of the individuals I interviewed, who included manufacturers, training agencies and individual instructors, felt that training still lacked consistency, training materials varied widely in quality, and there was some tension between RESA and the training agencies. These are some of the issues that RESA said they plan to address. The forum urged that agencies consider "currency" requirements for instructors, which is a new addition.

It is fair to say that "recreational rebreather training" (as distinct from technical training) is still in its infancy, as PADI begins to roll out its program, which it launched in 2011. However, there is significant technical training experience to draw from. Most of the individuals I interviewed prior to the forum believed that PADI would help raise the bar for rebreather training in terms of standards and also quality of training materials. The forum recognized and endorsed the concept of identifying "recreational" training as distinct from "technical" training because of the different operational, training and equipment needs.

15. There is no way to know how a rebreather will perform in the field without conducting manned and unmanned testing, which can determine performance under worst-case conditions.

16. Manufacturers should ensure that proper testing has been conducted before releasing their product to the market. The tests document performance over the entire range of conditions for which the rebreather is designed.

Though not all sport rebreather manufacturers have third-party testing certifications, and there is disagreement over which certifications are essential, the consensus of the community is that premarket third-party testing is critical to ensure that rebreathers are fit for its purpose. This was one of the findings of RF3. In addition, the forum encouraged that testing be made to conform to international standards where possible and the results be publically available.

17. In many circumstances the use of full-face masks and adherence to the buddy system can improve rebreather diver safety. It was also noted that the addition of an onboard CO_2 monitor would represent a great improvement in safety. [At the time there were no proven CO_2 monitors on the market.]

The use of full-face masks and/or mouthpiece-retaining straps have long been standard in military diving. The idea is that these might prevent the loss of the mouthpiece and subsequent drowning should the diver lose consciousness. The cause of death in most rebreather fatalities is drowning.

Full-face masks are not very suitable for sport-diving applications, can cause additional problems, and have not been adopted by the technical-diving community for open-circuit or rebreather diving. Mouthpiece-retainer straps were not mentioned at RF2, but a few individual divers across the world are currently experimenting with them. The importance of protecting divers from drowning was discussed at the forum in the efforts to improve safety, and as a result the forum identified the efficacy of using these devices, particularly a retaining strap, as a research question — i.e., whether a mouthpiece-retaining strap would provide protection of the airway in an unconscious rebreather diver.

Today there are several CO_2 monitoring devices, including thermal-sensing devices that measure the passage of the reaction front through the scrubber, various timers, for example, that estimate scrubber duration based on oxygen consumption, and gaseous sensors that can measure CO_2

breakthrough. The consensus among the people I interviewed suggest that these are important developments in improving rebreather safety, and more vendors seem to be offering CO_2 monitoring options with their units.

Though a number of rebreather fatalities occurred during solo dives, there has been no official community push to discourage solo rebreather diving. Even so, many individuals I spoke said that they believed it is a risky practice. There was little discussion of the issue at RF3. One well-known rebreather instructor and author said that divers should have at least "n" hours — I think it was 50 or 100 — before attempting solo rebreather diving.

18. There doesn't appear to be any unusual product liability problems that should keep rebreathers off the market, but regulatory concerns appear to be a more significant issue.

At the time of RF2, OSHA, which regulates the U.S. workplace, declined to grant a recreational exemption to instructors engaged in rebreather training. That meant that those who use rebreathers as employers/employees — for example, in dive instruction — fall under commercial-diving regulations until the issue can be resolved.

Since that time, the pressure felt by the sport-diving community from OSHA seems to have diminished significantly. I asked training-agency executives whether OSHA had granted an exemption for sport-diving/recreational rebreather use, and they said they did not know but that it is no longer an issue.

19. Developing a consumer market for rebreathers will take time. To be successful, the industry must move forward one step at a time, fulfill requirements, identify and document problems, and communicate with each other.

It has taken nearly 15 years, and the market, while not in its infancy, is still slowly developing. Unlike consumer electronic equipment, whose product life cycles are measured in months, diving equipment evolve much more slowly due to low volumes. The industry is moving ahead, and many people I spoke to say that they believe that with the advent of recreational rebreathers the market is once again at an inflection point — i.e., a point of relatively rapid change.

20. The forum consensus was that holding another rebreather forum would be desirable in the coming years to share experience and data gained since RF2.

That's what PADI, DAN, and the American Academy of Underwater Scientists did. They deserve big thanks from the community. The overwhelming consensus at the forum was that we should not wait another 15 years to have the next one.

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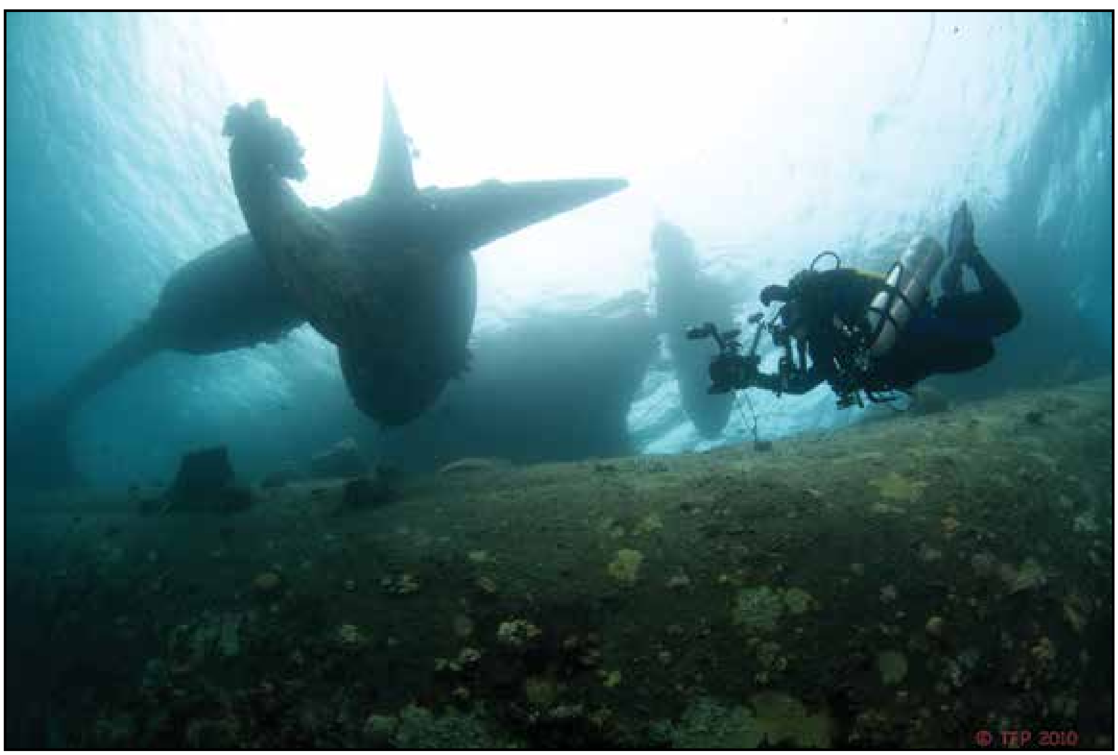

KMS Prinz Eugen Kwajalein Atoll Marshall Islands. Photo by Andrew Fock.

ANATOMY OF A REBREATHER DIVE

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INTRODUCTION

Rebreather Forum 3 was convened primarily as a platform for discussion of various issues that may have an impact on the safety of diving with rebreathers. It was attended by many expert presenters and rebreather divers who contributed to these discussions. However, it was recognized that the forum would also attract some divers who were not rebreather users but who were perhaps contemplating purchasing one or simply interested in learning about them. For this reason the program included a presentation on the basics of rebreather devices titled "Anatomy of a Rebreather Dive." The presentation is summarized here. It should be clear from the outset that the scope of this commentary is limited. It is not intended for trained rebreather divers who would find it lacking in depth. Nor is it intended to serve as a training tool for similar reasons. It is written to provide some basic grounding on the nature of rebreathers and how they are typically used in diving.

WHAT IS A REBREATHER?

Put as simply as possible, using a rebreather is analogous to breathing in and out of a plastic bag sealed over the mouth. Expired gas is not lost into the surrounding environment and is instead "rebreathed." Knowledge of simple physiology predicts two problems will quickly occur: the respired gas becomes hypoxic, and there is accumulation and rebreathing of carbon dioxide (CO_2). Breathing a hypoxic gas will eventually result in loss of consciousness, and breathing CO_2 may result in progressive symptoms as described in the physiology lecture. It follows that if we are going to rebreathe expired gas we must have a means of achieving two fundamental goals: removal of CO_2 from the expired gas and maintenance of safe oxygen levels in the inspired gas.

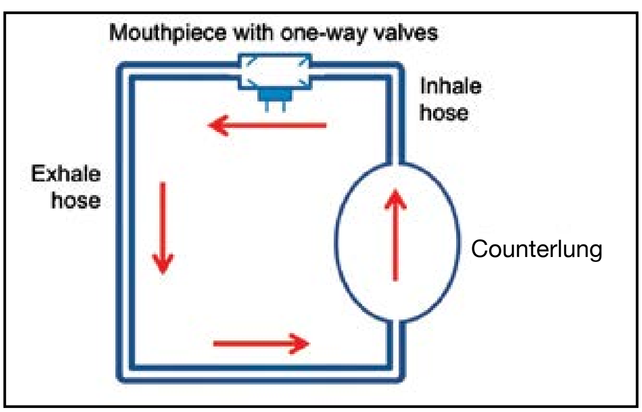

Figure 1. Simplified and stylized depiction of a basic rebreather circle circuit or "loop." Note the one-way valves in the mouthpiece that ensure unidirectional flow (indicated by arrows) around the loop.

A diving rebreather involves breathing in and out of a bag (referred to as a counterlung); in the modern context, this is almost invariably around a "circle circuit" or "loop," which comprises an exhale hose leading from the mouthpiece to the counterlung and an inhale hose leading from the counterlung back to the mouthpiece. Some rebreathers incorporate more than one counterlung (one for exhalation and one for inhalation), whereas others have only one. The concept is most conveniently represented by a single counterlung. One-way valves in the mouthpiece ensure that the flow around the loop is unidirectional (Figure 1). The mouthpiece contains a shut-off valve (dive/surface valve or DSV) so that the loop can be isolated from the environment when the mouthpiece is out of the mouth.

Removal of CO_2

Removal of exhaled CO_2 is the simpler of the two fundamental goals to achieve. The exhaled gas is passed through a canister (Figure 2) containing a CO_2 absorbent material such as soda lime (primarily a mixture of sodium hydroxide and calcium hydroxide, which reacts with CO_2 to produce calcium carbonate). A canister of soda lime has a finite capacity to absorb CO_2, and this is usually indicated to divers as a duration in hours. Not surprisingly, the more soda lime the canister contains, the longer the duration. However, the science of CO_2

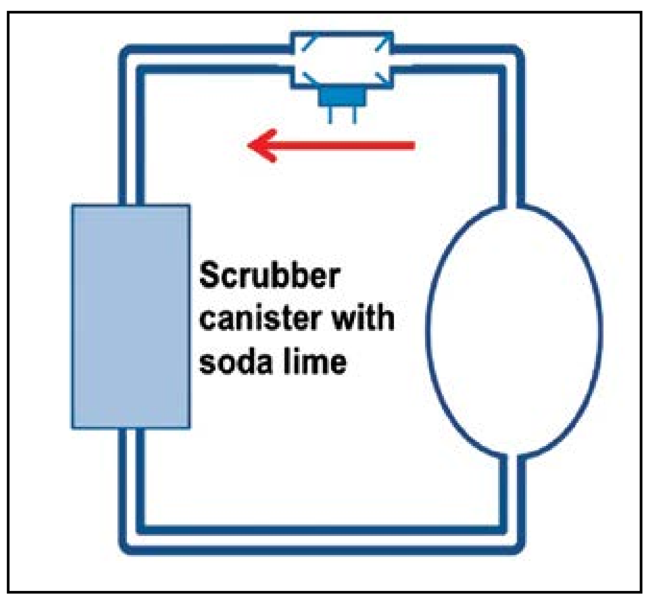

Figure 2. Simplified and stylized depiction of a basic rebreather circle circuit or "loop" with a CO_2 scrubber canister added.

absorption is complex, and canister duration can vary with exercise levels (and therefore CO_2 production), environmental temperature, depth, and multiple other factors. Moreover, a canister can fail from the outset if it is incorrectly packed with soda lime or the canister itself is incorrectly installed in the rebreather (or not installed at all), allowing CO_2 to bypass the absorbent material.

Maintenance of PO_2

Maintenance of a safe inspired pressure of oxygen PO_2 is more complicated. In everyday life in air (oxygen fraction ~0.21) at sea level (ambient pressure ~1 atm) humans inspire a pressure of oxygen (PO_2) of 0.21 atm. Deep technical divers attempt to maximize the fraction of inspired oxygen while maintaining a safe inspired PO_2 because this reduces inert gas absorption during the dive and accelerates inert gas elimination during decompression. As will be seen, this goal is facilitated by the use of rebreathers.

Pure oxygen rebreathers

The simplest means of maintaining the inspired PO_2 in a rebreather is to use only 100 percent oxygen in the loop. Oxygen is added to maintain the loop volume as depth and ambient pressure increases. Thus, the PO_2 in the loop will be equal to the ambient pressure and will change in direct relation to depth. (Note: It is necessary to flush nitrogen from the breathing bag before diving to avoid the risk of hypoxia at shallow depths in the event that there is enough residual nitrogen to ventilate the lungs after oxygen has been absorbed metabolically.) Depth is significantly limited by the threat of oxygen toxicity, which could occur if the diver was to venture too deep and inspire a high PO_2. Indeed, the maximum safe depth for unconstrained use of pure oxygen rebreathers is probably 20 ft (6 m; ambient pressure 1.6 atm abs, and inspired PO_2 of 1.6 atm) or even less.

Oxygen rebreathers have various means of introducing fresh gas into the loop. It can be as simple as a demand valve variant in which a valve is opened when the counterlung volume falls (either because depth increases or oxygen is consumed by the diver). Similarly it may be a manually operated valve activated by the diver when he notices the counterlung volume falling. Some units incorporate a constant mass flow (CMF) injector to bleed in a set amount of oxygen calculated to meet the requirements of normal metabolism at modest exercise. The design of a CMF injector ensures that the same number of oxygen molecules is added regardless of depth. A CMF system ensures that the diver does not have to activate a manual valve as often as he otherwise would. The stylized layout of an oxygen rebreather is shown in Figure 3.

If the diver wants to venture deeper than 20 ft (6 m), then pure oxygen cannot be used in the loop. Management of gas addition and maintenance of PO_2 thus becomes more complicated, and there are now many combinations and permutations of 'system' on the market. The following commentary will be largely limited to some illustrative examples of the more common systems.

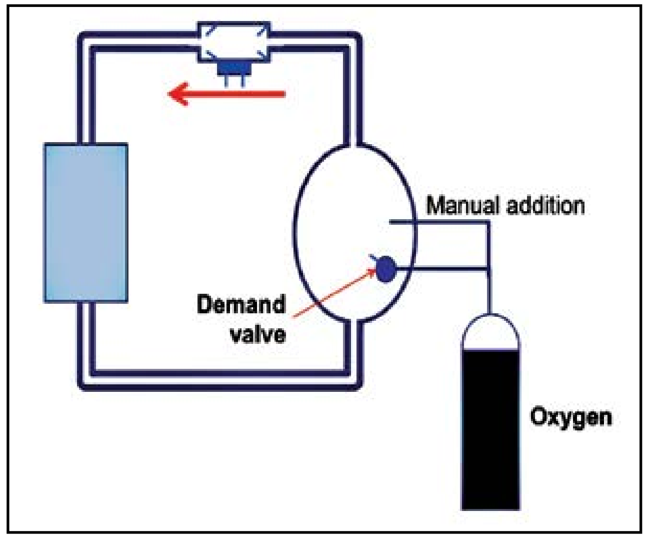

Figure 3. Simplified and stylized depiction of a pure oxygen rebreather. See text for explanation. Some of these devices also have a CMF injector.

Semiclosed-circuit rebreathers (SCRs)

The typical characteristic of SCRs is that they introduce sufficient premixed oxygen-containing gas into the loop to maintain the loop PO_2 at a safe level. The premixed gas is typically nitrox, which contains more oxygen than air but substantially less oxygen than pure oxygen. The obvious advantage over pure oxygen rebreathers is that the lower loop oxygen content allows the diver to venture deeper. The most common means of controlling fresh gas entry to the loop is a CMF injector. The amount of gas added is based on its oxygen content and assumptions around typical oxygen consumption during a dive. Almost invariably, for safety, an excess of gas is added to the loop, and this is vented through an overpressure valve, making SCRs less economical on gas consumption than closed-circuit rebreathers (see below). It should be apparent, however, that the when a premix of oxygen and inert gas is added to the loop but only the oxygen is consumed, the actual amount of oxygen (and therefore the PO_2) in the loop can vary significantly according to the diver's oxygen consumption. Under conditions of unexpectedly high exercise, the PO_2 will fall. In addition to a CMF injector, most SCRs also have a demand valve and/or manual bypass valve that allows addition of gas to the loop when needed, such as when descending. The stylized layout of an SCR is shown in Figure 4.

In some SCRs, particularly older models, the system is simply trusted to keep the inspired PO_2 within an acceptable range based on assumptions about oxygen consumption. More recently, SCR manufacturers or the users themselves have tended to put galvanic fuel cells in the loop that allow measurement of the PO_2 in real time during the dive. These cells are

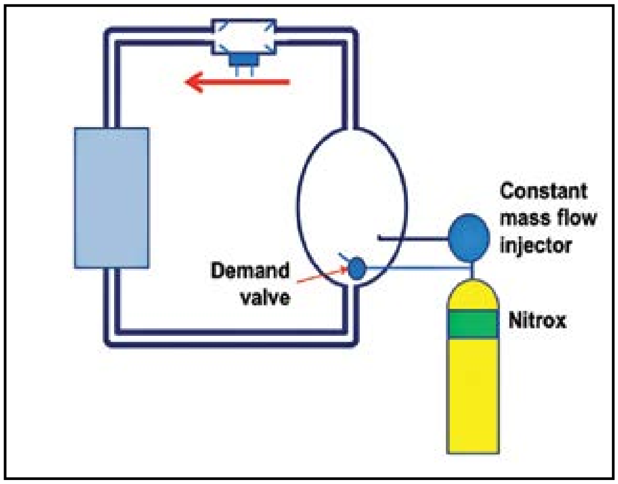

Figure 4. Simplified and stylized depiction of a semiclosed-circuit rebreather. See text for explanation. Most of these devices also have a manual injector.

mentioned further in discussion of closed-circuit rebreathers below. Measurement of the loop PO_2 is considered to improve the safety of SCRs, and it also facilitates more accurate evaluation of decompression requirements on decompression dives.

Closed-circuit rebreathers (CCRs)

The defining feature of virtually all CCRs is that pure oxygen is mixed with a diluent gas to produce a respired gas mix with a constant PO_2. For the inspired PO_2 to be constant across a range of depths, the fraction of oxygen in the mix must change. This is achieved in the CCR by the independent adjustment of oxygen addition to the loop in response to the PO_2. In electronic CCRs (eCCRs) an electronic control system performs this adjustment, and in manual CCRs (mCCRs) the user manually adds oxygen when necessary, usually to supplement basal oxygen addition by a CMF injector. Both scenarios require that the loop PO_2 is measured, and this is achieved by the use of galvanic fuel cells. These are effectively oxygen-powered batteries that produce a current in direct proportion to the PO_2 to which they are exposed, and this allows measurement and display of the PO_2 in the loop. It is well recognized that oxygen cells have a finite lifespan and are prone to inaccuracy and failure that may be difficult to predict or detect. Detailed discussion of these matters occurs elsewhere in the forum and is beyond the scope of this review. Suffice it to say that these issues dictate that most rebreathers contain multiple oxygen cells, with three being a common number.

Figure 5 shows a stylized layout of an eCCR. For convenience the oxygen cells are shown as though they reside in the counterlung, but this is never the case. The readings from the three cells are interpreted by the microprocessor according to a programmed algorithm. This program will include contingencies for how disagreement between cells is interpreted. For example, when the readings of all three cells are confluent they will be averaged to give the loop PO_2, but if one cell deviates from the other two by a threshold amount, then its reading will be ignored and those from the remaining cells will be averaged. These rules by which the microprocessor works are sometimes referred to as "voting logic." The diver tells the microprocessor what PO_2 he wishes to breathe. This is referred to as the PO_2 setpoint. When the PO_2 falls below the setpoint the microprocessor opens an electronic solenoid valve that bleeds oxygen into the loop until the setpoint is restored; hence the earlier reference to "constant PO_2" diving. The diver fulfills

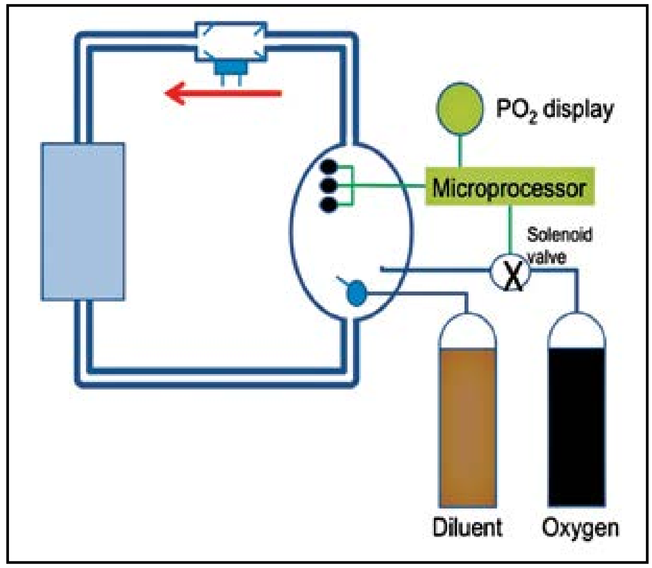

Figure 5. Simplified and stylized depiction of an eCCR. See text for explanation. Manual injectors for both oxygen and the diluent gas have been omitted for simplicity.

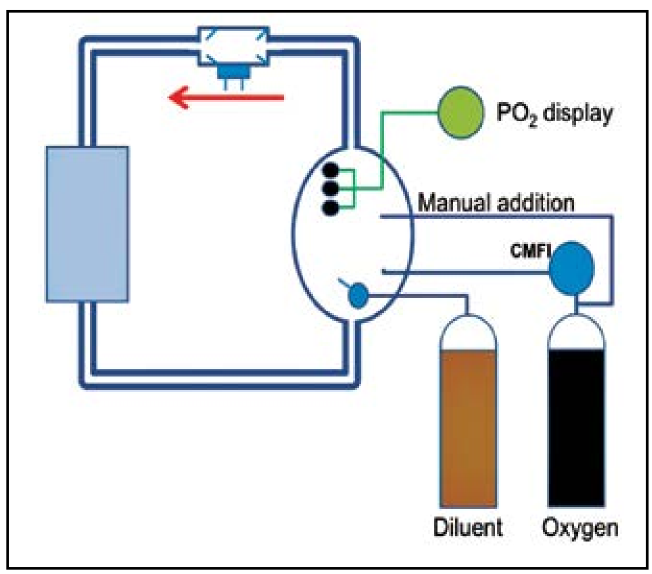

Figure 6. Simplified and stylized depiction of an mCCR. See text for explanation. Note that the oxygen cells are depicted as being sited in the counterlung, but this is never the case. A manual injector for diluent gas has been omitted for simplicity. CMFI = constant mass flow injector.

this function by using a manual oxygen addition valve in an mCCR (Figure 6). In both e- and mCCRs there is at least one display that allows the diver to see the PO_2 readings from the three cells. In most modern units there is a heads-up display (HUD) that depicts the PO_2 status of the rebreather and cell function is some way (usually color-coded LEDs), and there is frequently some form of audible alarm system to warn of problems and prompt the diver to look at his display.

There must be a diluent gas (so named because it dilutes the oxygen) because the rebreather should not be operated with pure oxygen at depths beyond 20 ft (6 m). Diluent gas is typically added to the loop automatically by a valve opened when the volume of the loop decreases (e.g., during descent). The diluent gas itself is chosen according to the nature of the dive. If the dive is within the normal recreational diving range (≤130 ft [40 m]), then it is common to use air. In this setting the rebreather blends air and oxygen in the loop to make nitrox. If a deep dive is contemplated, air is no longer a suitable diluent for the same reasons it is not suitable for deep diving on open-circuit: It contains too much oxygen, the nitrogen is narcotic, and the mix is too dense. In this case the diver will fill the diluent cylinder with either heliox or trimix, and the rebreather will blend it with oxygen to produce an appropriate mixed gas.

It would be technically possible to have only inert gas (e.g., nitrogen, helium, or a mixture of the two) in the diluent cylinder, but in practice this is never done. Most CCRs provide an open-circuit connection to their diluent cylinder so that the diver can breathe directly from it in the event of a rebreather failure. Clearly, this would be impossible if it contained no oxygen at all. There are several other "failure mode" drills and safety issues that would be compromised if the diluent contained no oxygen. Thus, the presence of some oxygen in the diluent cylinder is a safety feature. The diver must carefully consider the fraction of oxygen in the diluent mix, especially for deep dives. The diluent is there to dilute the oxygen so that the PO_2 can remain within safe limits at the planned depth. It will be of limited use if the diluent itself contains sufficient oxygen that its PO_2 will exceed the setpoint at the target depth.

ADVANTAGES OF REBREATHERS COMPARED TO OPEN-CIRCUIT DIVING

There are a number of advantages of rebreather diving when compared to open-circuit scuba diving, and these become most apparent when deep dives are undertaken. Of greatest importance, by not exhaling into the water divers markedly reduce their gas consumption (as was alluded to previously), and in addition the gas consumption is largely independent of depth. Descent to greater depths will consume a little more diluent to maintain loop volume, but unless there are numerous depth changes within the dive, this is minimal. Oxygen consumption is largely limited to the amount of gas metabolized, which is small. In contrast, a deep open-circuit dive consumes large amounts of gas, and this increases in direct proportion to the depth. As the price of helium increases and its availability declines this will make rebreathers an increasingly attractive, if not obligatory, tool for deep diving.

The constant PO_2 approach has the advantage of perpetual maintenance of the optimal safe fraction of oxygen in the mix (see Table 1) so that inert gas uptake is minimized during the dive and outgassing of inert gas is maximized during decompression. In contrast, an open-circuit gas mix can only be optimized for one depth. On a deep open-circuit dive where the depth is known it is possible to produce a mix that will result in the optimal fraction of inspired oxygen at that depth. Nevertheless, during decompression on open-circuit, there are inevitably periods during which the inspired fraction of oxygen is not optimized. This is illustrated in Figure 7, which contrasts the inspired PO_2 during decompression from a 295 ft (90 m; 10 atm abs) dive on a CCR and using open-circuit scuba (using trimix 13:47 [13 percent O_2, 47 percent He, balance N_2] as a bottom gas, and nitrox 36 and 100 percent oxygen for decompression). Both modalities produce an inspired PO_2 of 1.3 atm (widely considered the highest PO_2 that is safe for breathing over several hours) at 295 ft (90 m). In the rebreather, continuous adjustment of the fraction of inspired oxygen maintains a constant inspired PO_2 of 1.3 atm during the decompression. In contrast, on open-circuit this PO_2 is only achieved during decompression when gas switches are made, and the PO_2 is only maintained at the depth where the switch was made.

Table 1. The effect of running a constant PO_2 setpoint on the fraction of oxygen in the respired mix across a range of depths down to 295 ft (90 m). Note that the PO_2 setpoint at the surface is set at some level less than 1.0 atm (typically 0.7 atm) to stop the rebreather from continuously adding oxygen in an attempt to achieve a PO_2 setpoint that cannot be achieved at 1.0 atm ambient pressure.

Depth (m)	Pressure (atm abs)	PO2 set point (atm)	Fraction of oxygen in respired mix (%)
Surface	1	0.7	70
10	2	1.3	65
20	3	1.3	43
30	4	1.3	33
40	5	1.3	26
50	6	1.3	22
90	10	1.3	13

There are other advantages, such as the lack of bubbles, especially when diving an eCCR. This can be especially useful to photographers approaching wildlife and cave or wreck divers in fragile overhead environments. Because the reaction of CO_2 with soda lime is an exothermic reaction, rebreathers also ensure that the diver breathes warm, humidified gas — the opposite of what occurs on open-circuit scuba.

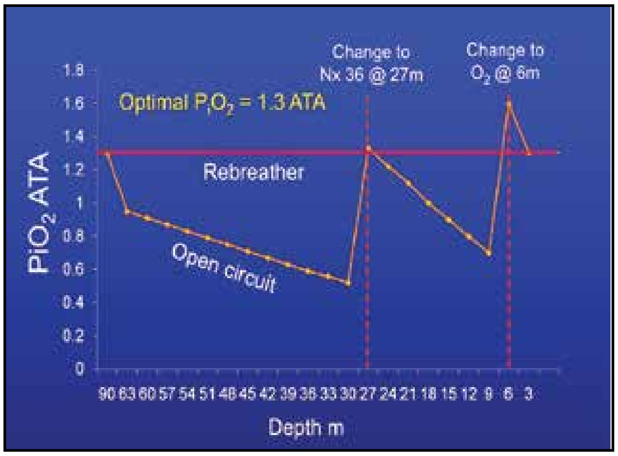

Figure 7. See text for explanation. An illustration of the contrast in PO_2 during ascent when using a CCR versus open-circuit scuba with intermittent gas changes. Note how the PO_2 constantly remains at 1.3 atm during the ascent on the rebreather but falls between gas switches during upward progress during ascent on open circuit.

Against all of the above is the extra purchase cost and the technical complexity associated with using a rebreather. The latter, when combined with human fallibility, provides fertile ground for error and accidents. Reviewing this issue is beyond the scope of this account, but it is dealt with in other papers both in these proceedings and elsewhere (Fock, 2013).

A REBREATHER DIVE

This account is an attempt to identify the key decisions and steps involved in planning and executing a deep rebreather dive, but the descriptions will be superficial. It is acknowledged that different divers will justifiably consider the various issues in different order and come to different solutions for the same problem. This commentary does not purport to describe a model of good practice.

Where necessary for context we will assume that the plan is to dive down a wall to 295 ft (90 m) and spend 20 minutes at that depth using an eCCR. The decompression will be spent ascending up the wall to the surface. Depending on the conditions, the shallow decompression stops will be spent either on the wall itself or hanging underneath a surface marker buoy a safe distance off the wall. The logistics of the procedure pertaining to surface support and personnel will not be considered further.

In the planning stages of a rebreather dive, one of the first decisions to make is what setpoint and diluent gas will be used. Once these are known, a decompression planning algorithm can be consulted and a dive plan constructed. As previously intimated, many divers will elect for a PO_2 setpoint of 1.3 atm since this appears safe for moderate duration dives (180 minutes to 100 percent CNS exposure on the NOAA oxygen clock). Although validated accounts of oxygen toxic seizures when breathing oxygen at this pressure are rare almost to the point of being apocryphal, some divers use lower setpoints either throughout the dive or especially during the more active bottom phase. Some then increase the setpoint during decompression when at rest. For simplicity we will adopt a plan that keeps the setpoint at 1.3 atm throughout.

The choice of diluent is driven by several considerations. First, the oxygen content must be low enough so as to be able to achieve the PO_2 setpoint at the target depth. Second, the nitrogen content must be low enough so as not to cause unacceptable narcosis at the target depth. Finally, the helium content should be high enough that the density of the respired gas will not cause respiratory difficulty. There are formulae for calculating these parameters, but they will not be discussed further here. In the present example, an oxygen fraction of 0.13 (13 percent) will allow achievement of an inspired PO_2 of 1.3 atm at 295 ft (90 m; 10 atm abs). A nitrogen fraction of 0.4 will result in an equivalent narcotic depth (as if diving air) of 141 ft (43 m). Some divers prefer a lower equivalent narcotic depth. Indeed, nitrogen can be omitted altogether, though many decompression planners penalize (possibly inappropriately [Doolette and Mitchell, 2013]) higher helium fractions by imposing longer decompressions. Since the rebreather will not modify a diluent gas with a PO_2 the same as setpoint at the target depth, we can assume that we will effectively breathe the diluent gas mix during the bottom time. Gas density calculations suggest that this mix (13 percent oxygen, 47 percent helium and 40 percent nitrogen [trimix 13:47]) will not be excessively dense when breathed at 10 ATA.

Having decided on a depth, bottom time, PO_2 setpoint and a diluent gas, the required decompression can be calculated using a planning tool with a constant PO_2 CCR capability. This is a valuable exercise to complete even if the diver intends to use a dive computer for real-time control of the decompression on the dive itself. If the latter is the case, then using a preplanning tool with the same algorithm as the intended dive computer is highly desirable. The decompression algorithm applied by the planning tool may be user adjustable for conservatism, and some tools provide a platform for multiple decompression algorithms from which the user can choose. Discussion of the choice of decompression algorithms and their manipulation by users has recently been reviewed elsewhere (Doolette and Mitchell, 2013). Table 2 shows an example of the output of one such tool: Multideco 4.04 by Ross Hemingway set to apply the Buhlmann ZHL16-B algorithm with gradient factors 40/75 to the present dive. The predicted run time is 112 minutes.

The diver should also use the decompression planner to formulate an open-circuit bailout ascent procedure. Bailout is gas carried in open-circuit scuba cylinders for use if the rebreather fails for any reason, and planning the nature and quantities of the gas to be carried follows usual open-circuit gas-planning principles with one caveat: The gas consumption will almost certainly be higher than normal (sometimes markedly so) when a diver bails off a rebreather in a stressful situation. Bailout planning will not be discussed in any further detail here. All gases (diluent, oxygen, bailout) must be mixed and analyzed by both the mixer and end user, and the cylinders must be clearly labeled with the contents and the maximum operating depth.

Table 2. One potential approach to decompression for a dive to 295 ft (90 m) for 20 minutes bottom time. The profile was generated using the Multideco 4.04 platform running the ZHL16-B algorithm with gradient factors 40/75. EAD = equivalent air depth; END = equivalent narcotic depth; Diluent 13/47 = trimix with 13 percent oxygen, 47 percent helium and 40 percent nitrogen. CNS = the proportion of the recommended central nervous system oxygen exposure according to the NOAA oxygen clock. OTUs = whole body oxygen toxicity units, mainly used as predictor of pulmonary oxygen toxicity.

MultiDeco 4.04 by Ross Hemingway,
ZHL code by Erik C. Baker.
Decompression model: ZHL16-B + GF
DIVE PLAN
Conservatism = GF 40/75

Dec to	90m	(5)	Diluent 13/47	0.70 SetPoint, 18m/min descent.
Level 90m		15:00(20)	Diluent 13/47	1.30 SetPoint, 41m ead, 43m end
Asc to 51m		(24)	Diluent 13/47	1.30 SetPoint, -9m/min ascent.
Stop at	51m	0:40 (25)	Diluent 13/47	1.30 SetPoint, 18m ead, 25m end
Stop at	48m	1:00 (26)	Diluent 13/47	1.30 SetPoint, 16m ead, 24m end
Stop at	45m	1:00 (27)	Diluent 13/47	1.30 SetPoint, 14m ead, 22m end
Stop at	42m	1:00 (28)	Diluent 13/47	1.30 SetPoint, 13m ead, 21m end
Stop at	39m	1:00 (29)	Diluent 13/47	1.30 SetPoint, 11m ead, 20m end
Stop at	36m	1:00 (30)	Diluent 13/47	1.30 SetPoint, 9m ead, 18m end
Stop at	33m	1:00 (31)	Diluent 13/47	1.30 SetPoint, 7m ead, 17m end
Stop at	30m	2:00 (33)	Diluent 13/47	1.30 SetPoint, 6m ead, 15m end
Stop at	27m	2:00 (35)	Diluent 13/47	1.30 SetPoint, 4m ead, 14m end
Stop at	24m	3:00 (38)	Diluent 13/47	1.30 SetPoint, 2m ead, 13m end
Stop at	21m	4:00 (42)	Diluent 13/47	1.30 SetPoint, 0m ead, 11m end
Stop at	18m	4:00 (46)	Diluent 13/47	1.30 SetPoint, 0m ead, 10m end
Stop at	15m	6:00 (52)	Diluent 13/47	1.30 SetPoint, 0m ead, 9m end
Stop at	12m	8:00 (60)	Diluent 13/47	1.30 SetPoint, 0m ead, 7m end
Stop at	9m	11:00(71)	Diluent 13/47	1.30 SetPoint, 0m ead, 6m end
Stop at	6m	15:00(86)	Diluent 13/47	1.30 SetPoint, 0m ead, 4m end
Stop at	3m	26:00(112)	Diluent 13/47	1.30 SetPoint, 0m ead
Surface		(112)	Diluent 13/47	-9m/min ascent.

OTU's this dive: 161
CNS Total: 60.7%

Assembly of the rebreather is a process that merits the utmost care and attention to detail. Ideally, it should take place in a clean, quiet, well-lit environment in which no distractions are anticipated. It should not be rushed, and no shortcuts should be taken. If the manufacturer has provided a checklist of crucial steps and checks, this should be used. Typically, the scrubber canister will be filled with soda lime and installed in the rebreather. The breathing hoses will be attached after the function of the one-way valves in the mouthpiece is checked. When watertight integrity of the loop is established, it is usually checked by testing whether it holds a positive and negative pressure without leaking. When assembly is complete, it is usual to check operation of the electronics (including battery power) and to calibrate the oxygen cells. This almost always involves exposing them to a known gas (air or oxygen) and ensuring that they respond in the predicted manner.

Assembly can be undertaken well before the dive, but positive and negative pressure checks and possibly calibration are often repeated immediately before it. Similarly, CCR divers are taught to undertake a five-minute "prebreathe" immediately prior to diving. This involves breathing on the fully functioning loop for five minutes while self-monitoring for symptoms of CO_2 toxicity (which would indicate that the CO_2 scrubber is faulty) and while watching the displays to confirm that the rebreather is functioning correctly (including maintaining an appropriate PO_2). For this purpose, virtually all eCCRs allow PO_2 setpoint switching so that a low setpoint can be adopted for surface use. If the dive setpoint (e.g., 1.3 atm) was used at the surface, an eCCR would keep adding oxygen in a futile attempt to bring the loop PO_2 up to this level. The surface setpoint is typically 0.7 atm, and this can be switched to the higher setpoint automatically by the CCR or manually by the diver during descent. The five-minute prebreathe, if conducted immediately prior to water entry, is an opportunity to run through other final checks such as all cylinder pressures, ensuring bailout cylinder shut-off valves are in the expected position and that the drysuit inflator is connected.

The diver typically enters the water breathing on the loop and with the rebreather set on the low setpoint. Once in the water, and in contrast to open-circuit scuba (where the regulator can just be removed and dropped), it is vital that the diver remain aware that the DSV must be closed if the rebreather mouthpiece is to be removed. Failure to do this will result in a loss of buoyancy (as gas is forced out of the counterlungs) and potentially flooding of the loop. It is germane that the surface at the start of a rebreather dive is a hazardous place. It is often a time of exertion (and higher oxygen consumption), so there is a significant risk of hypoxia if the rebreather is not functioning correctly. It is also the place where other problems may first become apparent (e.g., something leaking, something missing, need to assist others) with a resulting distraction from focus on the rebreather and its operation.

Descent is often interrupted early to perform a leak check with the buddy, and some divers pause at 20 ft (6 m) to flush the loop with pure oxygen, so check that all the oxygen cells respond appropriately to a known PO_2 (they should read 1.6 atm) that is above the PO_2 setpoint that will be subsequently used. This gives reassurance that the oxygen cells are not "current limited" (see elsewhere in these proceedings). During the remaining descent (which would be long on a 295-ft [90-m] dive), the rebreather diver is arguably more task-loaded than an open-circuit diver. Not only are there the usual tasks related to ear clearing, buoyancy control, drysuit inflation, maintaining situational awareness and monitoring progress (depth), the rebreather diver must also maintain a vigilant watch on the loop PO_2, manually add diluent to maintain loop volume if necessary, and remember to change the PO_2 setpoint from the surface setting if this is not done automatically.

On arrival at the bottom, the prudent rebreather diver will take a few moments to collect his or her thoughts, check that the setpoint is correct and that the rebreather appears to be functioning correctly. The dive can then proceed. In general (and when breathing dense gas at 295 ft [90 m] this would certainly apply), divers are advised not to try to exert heavily when rebreather diving. The external work of breathing imposed by the device itself along with any static lung loads arising as a result of counterlung position can impair ventilation and make CO_2 retention more likely. These matters are dealt with in detail in the physiology section. Rebreather dives should be as relaxed as possible.

During the bottom time itself several important contrasts with open-circuit diving become apparent:

- First, perfect buoyancy is harder to establish and maintain. This is because fine adjustments of buoyancy cannot be made by altering lung volume. Respired gas is simply exchanged with the counterlung, and the diver's net buoyancy does not change. Moreover, the counterlung volume may change with changes in depth and oxygen addition by the rebreather, and prior adjustments to wing and drysuit gas volumes to optimize buoyancy may be negated. This is especially true during ascent. For this reason CCR rebreather divers are taught to try to maintain an awareness of counterlung volume and to maintain it at the lowest volume necessary to take adequate breaths.
- Second, rebreather divers have to learn the discipline of only exhaling through the mouth. Any gas exhaled into the mask through the nose will be lost into the environment, and this can result in faster gas consumption than planned. This can be an unexpected challenge for some divers.
- Third, another discipline that rebreather divers must develop is checking the PO_2 display frequently throughout the dive. Heads-up displays and audible alarms should not be considered a justification for infrequent (or no) checks on the actual oxygen cell readings. Watching how the cells are behaving can result in problems being anticipated before they occur. Indeed, it is widely accepted that the defining mantra of rebreather diving is "KNOW YOUR PO_2."

Because of the greater challenges in maintaining neutral buoyancy, ascent from a deep rebreather dive (or any rebreather dive for that matter) is ideally conducted with reference up a wall or shot line. Ascent is a time of significant potential change in counterlung volume. Not only is there expansion as ambient pressure decreases, the rebreather will also be adding significant quantities of oxygen to maintain the PO_2 setpoint. To maintain minimal counterlung volume, the diver will be required to actively vent gas into the environment regularly during ascent. This is most easily achieved by exhaling through the nose. Ascent is also a time when there is a risk of hypoxia if there is any problem with the oxygen addition system, so it is not a time for lapses in vigilance around checking the PO_2.

Buoyancy control becomes even more challenging at the shallow stops because the proportional changes in volume of loop gas are much greater with small changes in depth (Boyle's Law). Hovering on the shallow stops is a skill that experienced rebreather divers acquire, but it can be quite a challenge. It is very easy to find oneself unexpectedly at the surface if there are lapses in concentration. At the final stop or stops (and thus at a safe depth), some divers functionally convert the rebreather to a pure oxygen unit by flushing the loop with oxygen. This saves some battery power because it reduces or eliminates the need for the solenoid valve to open as often. On completion of decompression and prior to the final ascent from the last stop to the surface, the PO_2 setpoint is switched back to a lower surface value (e.g., 0.7 atm) so that during the final ascent and on arrival at the surface the rebreather does not continuously add oxygen to the loop in a futile attempt to reach a setpoint it cannot achieve. When the diver arrives at the surface, the DSV must be closed before removal of the mouthpiece to avoid a significant sudden loss of buoyancy as gas is forced out of the counterlungs.

In the aftermath of diving, rebreathers require a considerably great degree of care and attention to detail during tear down than open-circuit scuba equipment. It is certainly more than a case of rinsing, drying, and storing.

CONCLUSION

Rebreathers are fabulous tools that have enabled divers to achieve targets involving deeper and longer dives than are practicable on open-circuit scuba. However, they are more complex and less forgiving devices that require a different mindset, aptitude and skill set than other forms of diving, and it is not surprising that there is evidence for a higher rate of fatalities during their use (Fock, 2013). It is hoped that the discussion that takes place over the remainder of the forum will help inform, and perhaps resolve, some of the controversies around relevant safety issues.

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Robert Cook admiring prolific growth on a wreck at Truk Lagoon. Photo by Simon Mitchell.

Rebreather divers visit the wreck of the USS Lamson *at Bikini Atoll. Photo Simon Mitchell.*

INTRODUCTION TO REBREATHER COMMUNITIES

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The closed-circuit rebreather (CCR) community panel presented the hows and whys of CCR technology use. Included were leading members of the military, scientific, film, recreational, technical, and cave CCR communities. Each representative discussed operations, choices, limitations, enhancements, and community-specific accident analysis and training. Why are CCRs important to each community? How and when are they used? Are there community-specific training needs outside what most of us consider normal rebreather training? Are there specific requirements for the units they use? Do the answers to any of these questions apply to the CCR diving community in general? Clearly, CCR employment is not one size fits all. What a mix it was!

USS Aaron Ward*, Solomon Islands. Photo by Andrew Fock.*

MILITARY DIVING

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Rebreathers are used in the U.S. military when a diver wants to avoid detection, whether that is detection by ordnance during underwater mine countermeasure operations or detection by security forces during combat swimmer operations. Figure 1 shows the three rebreather systems in the Department of Defense (DoD) used for these missions: the Viper, MK-16 Mod 1, and MK-25 (Draeger Lar V).

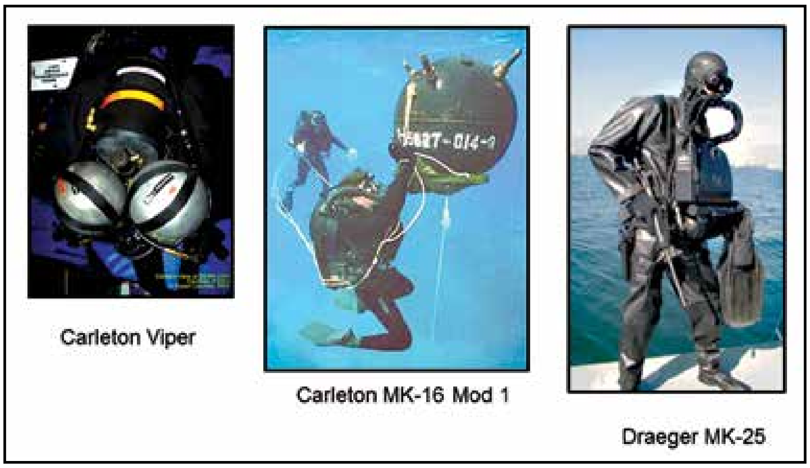

Figure 1. U.S. Navy rebreathers.

The MK-16 is a closed-circuit, electronically controlled, mixed-gas rebreather that uses nitrox to 150 fsw (46 msw) or heliox to 300 fsw (91 msw) (Figure 2). It is portable, easily deployed, supports communications, and has low-acoustic and nonmagnetic signatures, making it useful for underwater mine countermeasure operations. In 2011 the Navy made 3,336 MK-16 dives during which there were four diving accidents, including one fatality.

Figure 2. MK-16 Mod 1.

The MK-25 (Draeger Lar V) is a shallow O_2 rebreather used by combat swimmers in the Army Special Forces, Navy SEALs, and the U.S. Marine Corps (Figure 3). It is easily deployed, requires little support, has a long duration, is easy to swim, produces no bubbles, and has no acoustic signature, so a diver can get into denied areas undetected. The biggest disadvantage of an O_2 rebreather is the hazard of oxygen toxicity at depths much below 25 fsw (8 msw), although brief excursions as deep as 50 fsw (15 msw) are allowed. Many new procedures and desired missions include excursions that cannot be supported by the MK-25, and the Navy is looking for the next generation of combat swimmer rebreather. There were 11,441 MK-25 dives in 2011, most of them in training, with nine casualties, mostly arterial gas embolism (AGE) in trainees.

Finally, there is the Viper, a semiclosed-circuit rebreather using a gas mix of 60/40 O_2/N_2 for very shallow water (VSW) dives during mine countermeasures operations (Figure 4). For shallow water such as the surf zone, the MK-16 is not the best choice, but the Viper has low acoustic and low magnetic signatures, a lower profile, and is easier to dive in shallow water. The Viper's disadvantages include complex operation, depth limitation, hypoxia at shallow depths, and more bubbles than the MK-25 (but fewer than open-circuit). Only one command uses the Viper, making 247 dives in 2011 with no casualties.

Figure 3. MK-25.

Basic courses for the MK-16 and the MK-25 are taught in

Figure 4. Viper.

Panama City, FL, at the Naval Diving and Salvage Training Center (NDSTC). Navy SEALs (Coronado) and Army Special Forces (Key West) have their own dive basic schools for the MK-25. Advanced training for the MK-16 and MK-25 are conducted on the job and in the fleet. Viper training is at the only command that uses it.

The Navy made 105,463 dives using all types of equipment in 2011 with a total bottom time of 5,503,407 minutes during which there were 26 accidents or incidents (Table 1). Half these dives were with open-circuit scuba.

Figure 5 shows a summary of Navy diving casualties in 2007-2012. AGE was the most common injury, occurring primarily during Lar V training when students popped to the surface.

In summary, rebreathers provide mission-specific capabilities throughout the Navy and DoD. They enable access, provide stealth and support longer duration dives than would be possible with open-circuit. The increased risk of rebreather over open-circuit systems is mitigated through standardized training. Rebreathers will remain an important part of the U.S. Navy inventory for the foreseeable future.

Table 1. U.S. Navy diving activity, 2003-2013.

Unit	# of Dives	% of All Dives	# of Incidents	Incidents per 10,000 Dives
O/C scuba:	281,882	52.3	42	1.5
Mk-25	106,011	19.7	23	2.2
Mk-20	69,942	13.0	10	1.4
KM-37/Mk-21 Mod 1	56,521	10.5	25	4.4
Mk 16 Mod 1	20,995	3.9	19	9.0
Mk 16 Mod 0	981	0.2	6	61.2
VSW-Viper	946	0.2	0	0.0
Total	537,278	100.0	125	2.3

Mk-20 (AGA full facemask); KM-37Mk-21 (Hardhat surface supply).

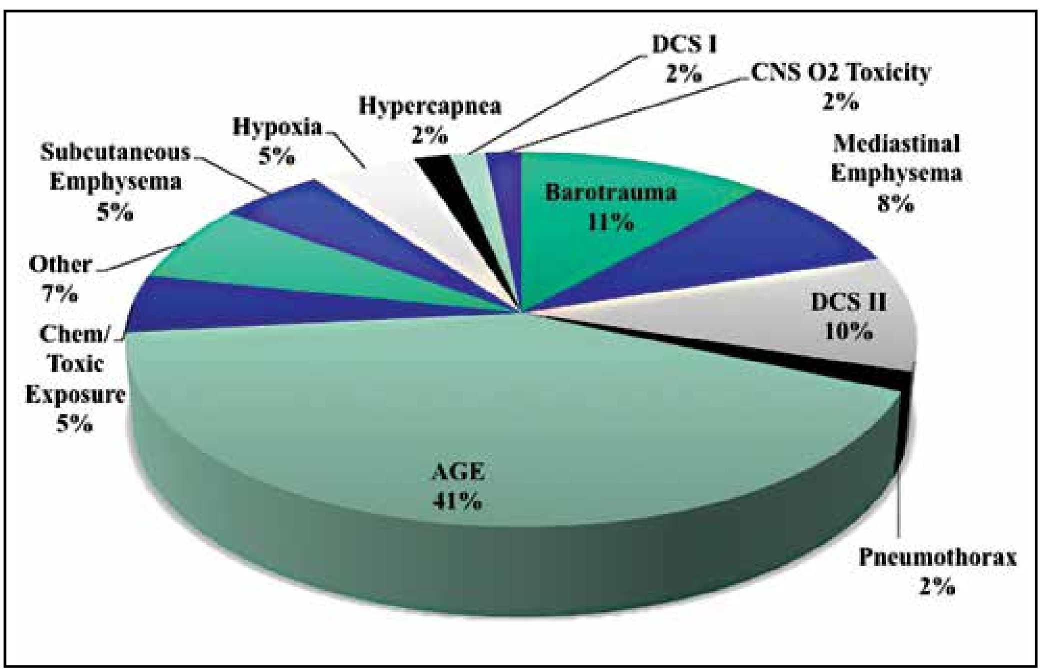

Figure 5. Dive casualties, 2007-2012.

REBREATHER PERSPECTIVE: THE SCIENTIFIC-DIVING COMMUNITY

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ABSTRACT

The American Academy of Underwater Sciences (AAUS) promulgates standards for the use of rebreathers as a research tool by the scientific-diving community. The current use of rebreathers is growing but remains at less than 1 percent of the overall annual scientific-diving activity of 128,000 dives. Broader integration of rebreathers will likely occur through unit cost reduction, simplified engineering and user interface, reduced (yet safe and defensible) training requirements, reduced unit preparatory and maintenance requirements and we hope production of a smaller, lighter package. The integration of rebreather technology into scientific-diving programs will gradually occur without compromising selection criteria and evaluation of divers based upon aptitude and discipline.

Keywords: AAUS, semiclosed-circuit, closed-circuit, OSHA, training

INTRODUCTION

Scientific diving is subject to U.S. Department of Labor Occupational Safety and Health Administration (OSHA) regulations. An exemption exists from the OSHA commercial diving standards (29 CFR 1910.402) if the diving is performed solely as a necessary part of a scientific, research or educational activity by employees whose sole purpose for diving is to perform scientific research tasks. Further, the scientific-diving exemption requires that the nature of the underwater activity meet the OSHA definition of scientific diving and is under the direction and control of a diving program utilizing a safety manual and a diving control board that meets certain specified criteria (Butler, 1996). Restrictions in diving technology for scientific diving use are not explicit in the OSHA standard, thus allowing for saturation/habitat diving, mixed-gas diving, and rebreather diving for scientific purposes.

AAUS is an organization of organizations, formalized in 1980 in response to OSHA's implementation of emergency commercial-diving standards. AAUS was organized to provide context to the scientific-diving community's system of self-regulation that existed since 1951. The mission of AAUS is to facilitate development of safe and productive scientific divers through education, research, advocacy and the advancement of standards for scientific-diving practices, certifications and operations. In 2012, 136 current organizational member programs represented more than 4,700 individual divers who logged more than 128,000 dives, not an insignificant annual data set.

Closed-circuit rebreathers (CCR) are not new technology and have historically been at home in the science community. The collaborative development by Walter Starck and John Kanwisher (Woods Hole Oceanographic Institution) of the Electrolung CCR with polariographic oxygen sensors came about through their chance meeting aboard Ed Link's diving research vessel in the Bahamas in 1968. In 1970 the General Electric MK 10 Mod III rebreather was used during the Tektite II saturation missions. The Harbor Branch/Biomarine CCR1000 was further developed with Gene Melton and used at Harbor Branch Oceanographic Institution for deep reef work in the 1970s. Bill Stone later developed the sophisticated Cis-Lunar rebreathers for scientific exploration in the 1980s.

CURRENT STATUS OF REBREATHERS

Rebreathers have a place in the scientific-diving community's underwater research toolbox, but their use to date has been limited as predominantly technical-diving instruments by a very small group of dedicated divers. To protect the safety and health of the scientific diver, current rebreathers mandate continuous attention and monitoring of complex life-support equipment functions that detract from the sole purpose of the dive mission: scientific underwater observations and data collections. The amount of time invested in training, predive and postdive equipment maintenance, and skill-level requirements is generally not realistic for broad application within the scientific-diving community. In an academic setting very little credit is given to scientists for their time spent in rebreather training and skills maintenance. Although rebreathers are not a new technology, the scientific-diving community's 60-year experience and exemplary safety record is predominantly based on open-circuit, compressed-air scuba.

The recognition by the diving industry that there is a finite universe of technical rebreather divers but that there is a market for recreational (non-technical) rebreathers, provides synergy with the needs of the scientific-diving community. Rebreathers are powerful tools for extended range and technical scientific diving but also exhibit extraordinary potential to optimize decompression, extend no-decompression bottom times and scientific productivity in depths less than 100 ft (30 m). Rebreathers also offer a reduced logistical footprint for scientific diving at remote sites, which is very attractive to the science community.

SCIENTIFIC REBREATHER APPLICATIONS AND DATA

Examples of current scientific use of rebreathers include animal behavioral observations, fish population assessments and bioacoustics studies, archaeological projects, mesophotic reef assessments and specimen collections, sea otter capture and release, scientific cave exploration and disturbance-sensitive under-ice manipulative experiments.

The majority of dives conducted by AAUS organizational members utilize open-circuit scuba (94 percent) and compressed air (84 percent) and do not involve required decompression (99 percent) (Table 1). There has been a gradual increase in rebreather diving activity since 1998, but it remains a very limited component of science activities (Figure 1) with much of this work being performed primarily by diving officers and a small contingent of diving scientists.

AAUS acknowledges the potential for CCR use in scientific diving programs yet currently the majority of scientific diving work occurs in 30 m (100 ft) of water or less, notwithstanding the scientific need and justification for expanding our working envelope to deeper depths (Lang and Smith, 2006).

AAUS REBREATHER STANDARDS

AAUS *Standards for Scientific Diving* are published at www.aaus.org. In addition to standards detailing diving program policies and administration, scientific diver training, equipment, and medical certification, the AAUS promulgates standards for Staged-Decompression Diving (Section 9.00), Mixed-Gas Diving (Section 10.00) and Rebreather Diving (Section 12.00: Oxygen, Semiclosed and Closed-Circuit). AAUS rebreather standards are reprinted in Appendix A.

Prior to undertaking rebreather training a scientist must complete the entry-level 100-hour scientific dive course, log at least 50 open-water dives and maintain a 100-ft (30-m) depth certification. AAUS depth authorizations allow scientific divers to work progressively deeper based on their accumulation of diving experience and proficiency. The prospective rebreather diver must demonstrate a firm understanding of gas laws, the use of enriched air nitrox, decompression, and mixed-gas protocols as appropriate.

Table 1. AAUS data on diving mode for calendar year 2010.

	Open-circuit	Rebreather	Hookah	Surface-supplied	Total
Organizational Members	117	21	21	22	125
Divers	4,591	87	299	286	4,769
Dives	120,047	1,291	2,654	3,417	127,409
Total Bottom Time (min)	5,003,312	61,884	145,001	110,889	5,321,086

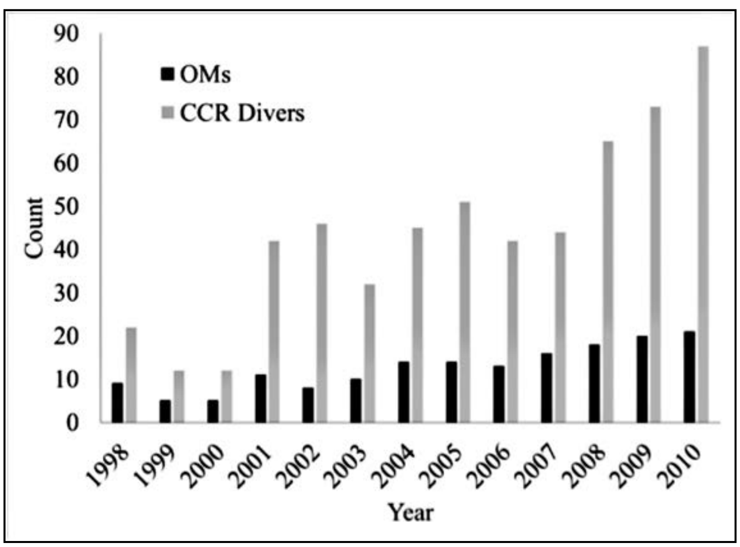

Figure 1. AAUS rebreather data: total number of divers logging rebreather dives and organizational member programs supporting rebreather diving (1998-2010).

CONCLUSIONS

AAUS standards are a living document subject to periodic review and revision as technology and our associated experience develops. These standards stipulate equipment selection criteria requiring that recognized quality-assurance/quality-control protocols be in place. Third-party testing and validation are important, and the recently formed Rebreather Education and Safety Association (RESA) should be helpful in this evaluation process.

Scientific diving programmatic considerations of rebreather implementation include specific rebreather unit selection criteria for standardized maintenance/training and proficiency requirements. The importance of manufacturer support and their timely response cannot be overstated. Diver selection criteria considerations will determine which divers can undertake rebreather training. Rebreathers will likely never become a tool that is as applicable to our entire community as the comparatively bulletproof and forgiving open-circuit scuba.

Looking forward, the scientific-diving community is not restricted by OSHA with respect to technology. We are free to use the best technology available to support our scientists in getting their work done. We look forward to the opportunity to work with manufacturers and training organizations and within our own community to design and implement rebreather standard operating procedures. The institution-based scientific-diving community has a very low tolerance for risk, which is reflected in our approach to the use of rebreather technology. Broader integration of rebreathers into scientific-diving programs will require unit cost reduction (though this is not an overwhelming hurdle), a simplified engineering and user interface, reduced (yet safe and defensible) training requirements given the transient nature of the scientific-diving community, reduced preparatory and maintenance requirements predive and postdive, and we hope a smaller, lighter package.

As an action item of this Rebreather Forum 3.0, AAUS will convene a Rebreather Colloquium at its 2012 annual scientific diving symposium to determine which of the RF3 findings can be integrated into our scientific-diving standards. AAUS will need to work on unit-specific training modules, maintenance requirements and strategies for keeping scientific divers training and skill levels current.

ACKNOWLEDGMENTS

We thank AAUS and the NOAA National Marine Sanctuaries for supporting the scientific-diving community and RF3 along with co-sponsoring organizations Divers Alert Network and the Professional Association of Diving Instructors.

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APPENDIX A
AAUS STANDARDS (Rev. 05/2013)

SECTION 12.0 REBREATHERS

This section defines specific considerations regarding the following issues for the use of rebreathers:

- Training and/or experience verification requirements for authorization
- Equipment requirements
- Operational requirements and additional safety protocols to be used

Application of this standard is in addition to pertinent requirements of all other sections of the AAUS Standards for Scientific Diving, Volumes 1 and 2. For rebreather dives that also involve staged decompression and/or mixed-gas diving, all requirements for each of the relevant diving modes shall be met. The Diving Control Board (DCB) reserves the authority to review each application of all specialized diving modes and include any further requirements deemed necessary beyond those listed here on a case-by-case basis. No diver shall conduct planned operations using rebreathers without prior review and approval of the DCB. In all cases, trainers shall be qualified for the type of instruction to be provided. Training shall be conducted by agencies or instructors approved by the Diving Safety Officer (DSO) and DCB.

12.10 Definitions and General Information

a) Rebreathers are defined as any device that recycles some or all of the exhaled gas in the breathing loop and returns it to the diver. Rebreathers maintain levels of oxygen and carbon dioxide that support life by metered injection of oxygen and chemical removal of carbon dioxide. These characteristics fundamentally distinguish rebreathers from open-circuit life-support systems in that the breathing-gas composition is dynamic rather than fixed.
   1) Advantages of rebreathers may include increased

gas-utilization efficiencies that are often independent of depth, extended no-decompression bottom times and greater decompression efficiency, and reduction or elimination of exhaust bubbles that may disturb aquatic life or sensitive environments.

2) Disadvantages of rebreathers include high cost and, in some cases, a high degree of system complexity and reliance on instrumentation for gas-composition control and monitoring, which may fail. The diver is more likely to experience hazardous levels of hypoxia, hyperoxia, or hypercapnia due to user error or equipment malfunction, conditions that may lead to underwater blackout and drowning. Inadvertent flooding of the breathing loop and wetting of the carbon-dioxide absorbent may expose the diver to ingestion of an alkaline slurry ("caustic cocktail").

3) An increased level of discipline and attention to rebreather system status by the diver is required for safe operation, with a greater need for self-reliance. Rebreather system design and operation varies significantly between make and model. For these reasons when evaluating any dive plan incorporating rebreathers, risk-management emphasis should be placed on the individual qualifications of the diver on the specific rebreather make and model to be used in addition to specific equipment requirements and associated operational protocols.

b) Oxygen Rebreathers. Oxygen rebreathers recycle breathing gas, consisting of pure oxygen, replenishing the oxygen metabolized by the diver. Oxygen rebreathers are generally the least complicated design but are normally limited to a maximum operation depth of 20 fsw (6 msw) due to the risk of unsafe hyperoxic exposure.

c) Semiclosed-Circuit Rebreathers. Semiclosed-circuit rebreathers (SCRs) recycle the majority of exhaled breathing gas, venting a portion into the water and replenishing it with a constant or variable amount of a single oxygen-enriched gas mixture. Gas addition and venting is balanced against diver metabolism to maintain safe oxygen levels by means that differ between SCR models, but the mechanism usually provides a semiconstant fraction of oxygen (FO_2) in the breathing loop at all depths, similar to open-circuit scuba.

d) Closed-Circuit Mixed-Gas Rebreathers. Closed-circuit mixed-gas rebreathers (CCRs) recycle all of the exhaled gas and replace metabolized oxygen via an electronically controlled valve, governed by electronic oxygen sensors. Manual oxygen addition is available as a diver override in case of electronic system failure. A separate inert gas source (diluent), usually containing primarily air, heliox, or trimix, is used to maintain oxygen levels at safe levels when diving below 20 fsw (6 msw). CCR systems operate to maintain a constant oxygen partial pressure (PO_2) during the dive, regardless of depth.

12.20 Prerequisites

Specific training requirements for use of each rebreather model shall be defined by DCB on a case-by-case basis. Training shall include factory-recommended requirements but may exceed this to prepare for the type of mission intended (e.g., staged decompression or heliox/trimix CCR diving).

a) Active scientific diver status, with depth qualification sufficient for the type, make, and model of rebreather, and planned application.

b) Completion of a minimum of 50 open-water dives on scuba.

c) For SCR or CCR, a minimum 100-fsw (30-msw) depth qualification is generally recommended to ensure the diver is sufficiently conversant with the complications of deeper diving. If the sole expected application for use of rebreathers is shallower than this, a lesser depth qualification may be allowed with the approval of the DCB.

d) Nitrox training. Training in use of nitrox mixtures containing 25-40 percent oxygen is required. Training in use of mixtures containing 40-100 percent oxygen may be required as needed for the planned application and rebreather system. Training may be provided as part of rebreather training.

Training

Successful completion of the following training program qualifies the diver for rebreather diving using the system on which the diver was trained, in depths of 130 fsw (40 msw) and shallower, for dives that do not require decompression stops, using nitrogen/oxygen breathing media.

a) Satisfactory completion of a rebreather training program authorized or recommended by the manufacturer of the rebreather to be used or other training approved by the DCB. Successful completion of training does not in itself authorize the diver to use rebreathers. The diver must demonstrate to the DCB or its designee that the diver possesses the proper attitude, judgment, and discipline to safely conduct rebreather diving in the context of planned operations.

b) Classroom training shall include:

   1) A review of those topics of diving physics and physiology, decompression management, and dive planning included in prior scientific diver, nitrox, staged decompression and/or mixed-gas training, as they pertain to the safe operation of the selected rebreather system and planned diving application.

   2) In particular, causes, signs and symptoms, first aid, treatment and prevention of the following must be covered: hyperoxia (central nervous system [CNS] and pulmonary oxygen toxicity), middle-ear oxygen absorption syndrome (oxygen ear), hyperoxia-induced myopia, hypoxia, hypercapnia, inert gas narcosis, and decompression sickness

3) Rebreather-specific information required for the safe and effective operation of the system to be used, including:
   - System design and operation, including:
   - Counterlung(s)
   - CO_2 scrubber
   - CO_2 absorbent material types, activity characteristics, storage, handling and disposal
   - Oxygen control system design, automatic and manual
   - Diluent control system, automatic and manual (if any)
   - Predive set-up and testing
   - Postdive breakdown and maintenance
   - Oxygen exposure management
   - Decompression management and applicable decompression tracking methods
   - Dive operations planning
   - Problem recognition and management, including system failures leading to hypoxia, hyperoxia, hypercapnia, flooded loop, and caustic cocktail
   - Emergency protocols and bailout procedures

Practical Training (with model of rebreather to be used)

a) A minimum number of hours of underwater time.
b) Amount of required in-water time should increase proportionally to the complexity of rebreather system used.
c) Training shall be in accordance with the manufacturer's recommendations.

Practical Evaluations

Upon completion of practical training, the diver must demonstrate to the DCB or its designee proficiency in predive, dive, and postdive operational procedures for the particular model of rebreather to be used. Skills shall include, at a minimum:

- Oxygen control system calibration and operation checks
- Carbon dioxide absorbent canister packing
- Supply gas cylinder analysis and pressure check
- Test of one-way valves
- System assembly and breathing-loop leak testing
- Predive breathing to test system operation
- In-water leak checks
- Buoyancy control during descent, bottom operations, and ascent
- System monitoring and control during descent, bottom operations, and ascent
- Proper interpretation and operation of system instrumentation (PO_2 displays, dive computers, gas supply pressure gauges, alarms, etc., as applicable)
- Unit removal and replacement on the surface.

- Bailout and emergency procedures for self and buddy, including:
  - System malfunction recognition and solution
  - Manual system control
  - Flooded breathing loop recovery (if possible)
  - Absorbent canister failure
  - Alternate bailout options
  - Symptom recognition and emergency procedures for hyperoxia, hypoxia, and hypercapnia
  - Proper system maintenance, including:
    - Full breathing-loop disassembly and cleaning (mouthpiece, check-valves, hoses, counterlung, absorbent canister, etc.)
    - Oxygen sensor replacement (for SCR and CCR)
    - Other tasks required by specific rebreather models

Written Evaluation

A written evaluation approved by the DCB with a predetermined passing score, covering concepts of both classroom and practical training, is required.

Supervised Rebreather Dives

Upon successful completion of open-water training dives, the diver is authorized to conduct a series of supervised rebreather dives during which the diver gains additional experience and proficiency.

a) Supervisor for these dives should be the DSO or designee and should be an active scientific diver experienced in diving with the make/model of rebreather being used.
b) Dives at this level may be targeted to activities associated with the planned science diving application. See the following table for number and cumulative water time for different rebreather types.

Type	Pool/Confined Water	O/W Training	O/W Supervised
Oxygen rebreather	1 dive, 90 min	4 dives, 120 min*	2 dives, 60 min
Semiclosed-circuit	1 dive, 90-120 min	4 dives, 120 min**	4 dives, 120 min
Closed-circuit	1 dive, 90-120 min	8 dives, 380 min***	4 dives, 240 min

* Dives should not exceed 20 fsw (6 msw).
** First two dives should not exceed 60 fsw (18 msw). Subsequent dives should be at progressively greater depths, with at least one dive in the 80-100 fsw (24-30 msw) range.
*** Total underwater time (pool and open water) of approximately 500 minutes. First two open water dives should not exceed 60 fsw (18 msw). Subsequent dives should be at progressively greater depths, with at least two dives in the 100-130 fsw (30-40 msw) range.

c) Maximum ratio of divers per designated dive supervisor is 4:1. The supervisor may dive as part of the planned operations.

Extended Range, Required Decompression and Helium-Based Inert Gas

Rebreather dives involving operational depths in excess of 130 fsw (40 msw), requiring staged decompression, or using diluents containing inert gases other than nitrogen are subject to additional training requirements, as determined by DCB on a case-by-case basis. Prior experience with required decompression and mixed-gas diving using open-circuit scuba is desirable but is not sufficient for transfer to dives using rebreathers without additional training.

a) As a prerequisite for training in staged decompression using rebreathers, the diver shall have logged a minimum of 25 hours of underwater time on the rebreather system to be used, with at least 10 rebreather dives in the 100-130 fsw (30-40 msw) range.
b) As a prerequisite for training for use of rebreathers with gas mixtures containing inert gas other than nitrogen, the diver shall have logged a minimum of 50 hours of underwater time on the rebreather system to be used and shall have completed training in stage decompression methods using rebreathers. The diver shall have completed at least 12 dives requiring staged decompression on the rebreather model to be used, with at least four dives near 130 fsw (40 msw).
c) Training shall be in accordance with standards for required-decompression and mixed-gas diving, as applicable to rebreather systems, starting at the 130 fsw (40 msw) level.

Maintenance of Proficiency

a) To maintain authorization to dive with rebreathers, an authorized diver shall make at least one dive using a rebreather every eight weeks. For divers authorized for the conduct of extended range, stage decompression or mixed-gas diving, at least one dive per month should be made to a depth near 130 fsw (40 msw), practicing decompression protocols.
b) For a diver in arrears, the DCB shall approve a program of remedial knowledge and skill tune-up training and a course of dives required to return the diver to full authorization. The extent of this program should be directly related to the complexity of the planned rebreather diving operations.

12.30 Equipment Requirements
General Requirements

a) Only those models of rebreathers specifically approved by DCB shall be used.
b) Rebreathers should be manufactured according to acceptable quality-control/quality-assurance protocols, as evidenced by compliance with the essential elements of ISO 9004. Manufacturers should be able to provide to the DCB supporting documentation to this effect.
c) Unit performance specifications should be within acceptable levels as defined by standards of a recognized authority (CE, U.S. Navy, Royal Navy, NOAA, etc.)
d) Prior to approval, the manufacturer should supply the DCB with supporting documentation detailing the methods of specification determination by a recognized third-party testing agency, including unmanned and manned testing. Test data should be from a recognized, independent test facility.
e) The following documentation for each rebreather model to be used should be available as a set of manufacturer's specifications. These should include:
    - Operational depth range
    - Operational temperature range
    - Breathing-gas mixtures that may be used
    - Maximum exercise level that can be supported as a function of breathing gas and depth
    - Breathing-gas supply durations as a function of exercise level and depth
    - CO_2 absorbent durations as a function of depth, exercise level, breathing gas, and water temperature
    - Method, range and precision of inspired PO_2 control as a function of depth, exercise level, breathing gas, and temperature
    - Likely failure modes and backup or redundant systems designed to protect the diver if such failures occur
    - Accuracy and precision of all readouts and sensors
    - Battery duration as a function of depth and temperature
    - Mean time between failures of each subsystem and method of determination
f) A complete instruction manual is required, fully describing the operation of all rebreather components and subsystems as well as maintenance procedures.
g) A maintenance log is required. The unit maintenance shall be up to date based upon manufacturer's recommendations.

Minimum Equipment

a) A surface/dive valve in the mouthpiece assembly, allowing sealing of the breathing loop from the external environment when not in use.
b) An automatic gas-addition valve so that manual volumetric compensation during descent is unnecessary.
c) Manual gas-addition valves so that manual volumetric compensation during descent and manual oxygen addition at all times during the dive are possible.
d) The diver shall carry alternate life-support capability (open-circuit bailout or redundant rebreather) sufficient to allow the solution of minor problems and allow reliable access to a preplanned alternate life-support system.

Oxygen Rebreathers

Oxygen rebreathers shall be equipped with manual and automatic gas-addition valves.

Semiclosed-Circuit Rebreathers

SCRs shall be equipped with at least one manufacturer-approved oxygen sensor sufficient to warn the diver of impending hypoxia. Sensor redundancy is desirable but not required.

Closed-Circuit Mixed-Gas Rebreathers

a) CCR shall incorporate a minimum of three independent oxygen sensors.
b) A minimum of two independent displays of oxygen sensor readings shall be available to the diver.
c) Two independent power supplies in the rebreather design are desirable. If only one is present, a secondary system to monitor oxygen levels without power from the primary battery must be incorporated.
d) CCR shall be equipped with manual diluent- and oxygen-addition valves to enable the diver to maintain safe oxygen levels in the event of failure of the primary power supply or automatic gas-addition systems.
e) Redundancies in onboard electronics, power supplies, and life-support systems are highly desirable.

12.40 Operational Requirements
General Requirements

a) All dives involving rebreathers must comply with applicable operational requirements for open-circuit scuba dives to equivalent depths.
b) No rebreather system should be used in situations beyond the manufacturer's stated design limits (dive depth, duration, water temperature, etc.)
c) Modifications to rebreather systems shall be in compliance with manufacturer's recommendations.
d) Rebreather maintenance is to be in compliance with manufacturer's recommendations including sanitizing, replacement of consumables (sensors, CO_2 absorbent, gas, batteries, etc.) and periodic maintenance.
e) Dive Plan. In addition to standard dive plan components stipulated in AAUS Section 2.0, all dive plans that include the use of rebreathers must include, at minimum, the following details:
    - Information about the specific rebreather model to be used
    - Make, model, and type of rebreather system
    - Type of CO_2 absorbent material
    - Composition and volume(s) of supply gases
    - Complete description of alternate bailout procedures to be employed, including manual rebreather operation and open-circuit procedures
    - Other specific details as requested by DCB

Buddy Qualifications

a) A diver whose buddy is diving with a rebreather shall be trained in basic rebreather operation, hazard identification, and assist/rescue procedures for a rebreather diver.
b) If the buddy of a rebreather diver is using open-circuit scuba, the rebreather diver must be equipped with a means to provide the open-circuit scuba diver with a sufficient supply of open-circuit breathing gas to allow both divers to return safely to the surface.

Oxygen Exposures

a) Planned oxygen partial pressure in the breathing gas shall not exceed 1.4 ata at depths greater than 30 ft (9 m).
b) Planned oxygen partial pressure setpoint for CCR shall not exceed 1.4 ata. Setpoint at depth should be reduced to manage oxygen toxicity according to the NOAA oxygen exposure limits.
c) Oxygen exposures should not exceed the NOAA oxygen single and daily exposure limits. Both CNS and pulmonary (whole-body) oxygen exposure indices should be tracked for each diver.

Decompression Management

a) DCB shall review and approve the method of decompression management selected for a given diving application and project.
b) Decompression management can be safely achieved by a variety of methods, depending on the type and model of rebreather to be used. The following is a general list of methods for different rebreather types:
    1) Oxygen rebreathers: Not applicable.
    2) SCR (presumed constant FO_2):
        - Use of any method approved for open-circuit scuba diving breathing air, above the maximum operational depth of the supply gas.
        - Use of open-circuit nitrox dive tables based upon expected inspired FO_2. In this case, contingency air dive tables may be necessary for active-addition SCRs in the event that exertion level is higher than expected.
        - Equivalent air depth correction to open-circuit air dive tables, based upon expected inspired FO_2 for planned exertion level, gas supply rate, and gas composition. In this case, contingency air dive tables may be necessary for active-addition SCRs in the event that exertion level is higher than expected.
    3) CCR (constant PO_2):
        - Integrated constant PO_2 dive computer
        - Non-integrated constant PO_2 dive computer
        - Constant PO_2 dive tables
        - Open-circuit (constant FO_2) nitrox dive computer, set to inspired FO_2 predicted using PO_2 setpoint at the maximum planned dive depth
        - Equivalent air depth (EAD) correction to standard open-circuit air dive tables, based on the inspired FO_2 predicted using the PO_2 setpoint at the maximum planned dive depth
        - Air dive computer, or air dive tables used above the maximum operating depth (MOD) of air for the PO_2 setpoint selected

Maintenance Logs, CO_2 Scrubber Logs, Battery Logs, and Predive and Postdive Checklists

Logs and checklists will be developed for the rebreather used and will be used before and after every dive. Diver shall indicate by initialing that checklists have been completed before and after each dive. Such documents shall be filed and maintained as permanent project records. No rebreather shall be dived that has failed any portion of the predive check or is found to not be operating in accordance with manufacturer's specifications. Predive checks shall include:

- Gas supply cylinders full
- Composition of all supply and bailout gases analyzed and documented
- Oxygen sensors calibrated
- Carbon-dioxide canister properly packed
- Remaining duration of canister life verified
- Breathing loop assembled
- Positive and negative pressure leak checks
- Automatic volume-addition system working
- Automatic oxygen-addition systems working
- Prebreathe system for three minutes (five minutes in cold water) to ensure proper oxygen addition and carbon-dioxide removal (be alert for signs of hypoxia or hypercapnia)
- Other procedures specific to the model of rebreather used
- Documentation of ALL components assembled
- Complete predive system check performed
- Final operational verification immediately before entering the water:
  - PO_2 in the rebreather is not hypoxic
  - Oxygen-addition system is functioning;
  - Volumetric addition is functioning
  - Bailout life support is functioning

Alternate Life-Support System

The diver shall have reliable access to an alternate life-support system designed to safely return the diver to the surface at normal ascent rates, including any required decompression in the event of primary rebreather failure. The complexity and extent of such systems are directly related to the depth/time profiles of the mission. Examples of such systems include, but are not limited to:

a) Open-circuit bailout cylinders or sets of cylinders, either carried or prepositioned
b) Redundant rebreather
c) Prepositioned life-support equipment with topside support

CO_2 Absorbent Material

a) CO_2 absorption canister shall be filled in accordance with the manufacturer's specifications.
b) CO_2 absorbent material shall be used in accordance with the manufacturer's specifications for expected duration.
c) If CO_2 absorbent canister is not exhausted and storage between dives is planned, the canister should be removed from the unit and stored sealed and protected from ambient air, to ensure the absorbent retains its activity for subsequent dives.
d) Long-term storage of carbon-dioxide absorbents shall be in a cool, dry location in a sealed container. Field storage must be adequate to maintain viability of material until use.

Consumables (e.g., batteries, oxygen sensors, etc.)

Other consumables (e.g., batteries, oxygen sensors, etc.) shall be maintained, tested, and replaced in accordance with the manufacturer's specifications.

Unit Disinfections

The entire breathing loop, including mouthpiece, hoses, counterlungs, and CO_2 canister, should be disinfected periodically according to manufacturer's specifications. The loop must be disinfected between each use of the same rebreather by different divers.

12.50 Oxygen Rebreathers

a) Oxygen rebreathers shall not be used at depths greater than 20 ft (6 m).
b) Breathing loop and diver's lungs must be adequately flushed with pure oxygen prior to entering the water on each dive. Once done, the diver must breathe continuously and solely from the intact loop, or reflushing is required.
c) Breathing loop shall be flushed with fresh oxygen prior to ascending to avoid hypoxia due to inert gas in the loop.

12.60 Semiclosed-Circuit Rebreathers

a) The composition of the injection gas supply of a semiclosed rebreather shall be chosen such that the partial pressure of oxygen in the breathing loop will not drop below 0.2 ata, even at maximum exertion at the surface.
b) The gas-addition rate of active addition SCRs (e.g., Draeger Dolphin and similar units) shall be checked before every dive to ensure it is balanced against expected workload and supply gas FO_2.
c) The intermediate pressure of supply gas delivery in active-addition SCRs shall be checked periodically in compliance with manufacturer's recommendations.
d) Maximum operating depth shall be based upon the FO_2 in the active supply cylinder.
e) Prior to ascent to the surface the diver shall flush the breathing loop with fresh gas or switch to an open-circuit system to avoid hypoxia. The flush should be at a depth of approximately 30 fsw (9 msw) during ascent on dives deeper than 30 fsw (9 msw) and at bottom depth on dives 30 fsw (9 msw) and shallower.

12.70 Closed-Circuit Rebreathers

a) The FO_2 of each diluent gas supply used shall be chosen so that if breathed directly while in the depth range for which its use is intended, it will produce an inspired PO_2 greater than 0.20 ata but no greater than 1.4 ata.
b) Maximum operating depth shall be based on the FO_2 of the diluent in use during each phase of the dive so as not to exceed a PO_2 limit of 1.4 ata.
c) Divers shall monitor both primary and secondary oxygen display systems at regular intervals throughout the dive to verify that readings are within limits, that redundant displays are providing similar values, and whether readings are dynamic or static (as an indicator of sensor failure).
d) The PO_2 setpoint shall not be lower than 0.4 ata or higher than 1.4 ata.

USS Aaron Ward*, Solomon Islands. Photo by Andrew Fock.*

CINEMATOGRAPHY

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LONG

My experience is mostly with documentary filmmaking where you use closed-circuit as opposed to a studio tank when open-circuit is usually adequate. On open-circuit if you suddenly find yourself at 300 psi (21 bar) and have to surface just as the great white sharks arrive to play with the whales — damn! This is the only time in history it is going to happen, and you miss the shot. Documentary filmmaking, first and foremost, is about natural history and storytelling — we are there to film the environment, the animals, behavior and natural interactions. You use a closed-circuit rebreather (CCR) for that because open-circuit is finite. You are there to film the timeless, and you need as much time as you can get in the environment. Filming wildlife on land or underwater often requires hours of waiting to find the shots that tell the creature's story. You sit and sit and sit and wait before a burst of frenetic activity — not ideal for a closed-circuit dive where everything should be consistent and smooth. That's not always in the cards for a filmmaker.

QUIET

Silence is king. Open-circuit is always noisy. During a recent job on a shallow wreck, I was on closed-circuit with some open-circuit divers in the group. After about an hour, the others surfaced to change tanks, and within 5-10 minutes the school of giant grouper we were waiting for arrived. What an interaction! Then they departed as fast as they appeared, and what did I hear — the open-circuit train coming down from the surface. The bottom line is animals do not like noise. You are not going to film "skittish" wildlife on open-circuit. You will get something but not the good stuff, and you will have producers, directors, and people paying lots of money who do not want to hear that the animals never showed up. They want the shots!

Figure 1. Evan Kovacs filming humpbacks. Photo by Becky Kagan.

DEEP

Filming can often be deep, not necessarily technically deep, but 70-100 ft (21-30 m) can be deep enough, particularly in a remote part of the world. That is where closed-circuit really shines. The gas and dive team logistics are so much simpler. For a deep project in the Pacific, I would have needed about 100 bottles of helium and a container ship to haul it. It was not going to happen. It was financially impractical without closed-circuit. Closed-circuit gives you freedom to experiment, adapt, and improvise based on the developing situation.

Figure 2. Evan Kovacs prepping for a dive on the Britannic. *Photo by Leigh Bishop.*

COMPLICATED

Both the life-support and camera systems are complicated, and the camera can be massive, weighing about 200 lbs (90 kg) on the surface and the size of a table. How do you train for something like that? There is no training for cinematographers other than experience. The most important rule is that you are a diver first and a photographer second. When you get "camera disease" and forget that, and all of us do it, you will miss things and may not be lucky enough to come back. Put down the camera, focus, and get back to rebreather basics.

TRAINING

You take cave training, you study with a wreck instructor, you do lots of training with experienced people all while diving closed-circuit. But it is so easy to forget to monitor your PO_2 when you are behind the lens and the creative spirit hits. The blinders come on, and it happens to everybody. I have been close to dying because I did not know my PO_2. On one dive, I was wearing a heads-up display that I could not see. The dive was to about 250 ft (76 m); around 60-70 ft (18-21 m) on ascent, the rebreather stopped working, my vision disappeared, and I dropped the camera. A training reflex made me hit my diluent valve, and my great support team pulled me out, or I would not be here now. That scared the hell out of me, and for my next dive I mounted the secondary display right up where I could see it. I never wanted that to happen again. I am not sure how you to train for excessive multitasking. Maybe people who survive have years of experience in diverse areas from caves to wrecks to reefs. Or maybe you get years of experience by surviving.

Figure 4. Evan Kovacs filming Eagles Nest with Richie Kohler. Photo by Becky Kagan.

HYPERBARIC MYOPIA

To prepare for the meeting, I was asked to talk to some fellow cameramen about hyperoxic myopia. This is a form of oxygen toxicity that is reported by patients undergoing hyperbaric oxygen (HBO) therapy in which nearsightedness develops after many HBO treatments. In the late 1990s a well-known cinematographer developed vision problems after several weeks of diving for up to four hours a day with a 1.3 atm PO_2. Fortunately, his vision returned to normal after a month out of the water. This was the first such report in a diver. Cinematographers commonly spend long periods underwater for several weeks breathing high PO_2. I had never heard of hyperoxic myopia or been affected myself, although I have certainly done lots of high-PO_2 diving. In casual conversation, I asked about 10 cinematographers if they had noticed any such issues and was surprised that four reported having extreme vision problems after several weeks of high-PO_2 diving. They did not go to a doctor, and their vision progressively returned to normal.

Figure 3. Keith Meverden using WHOI mosaic rig. Photo by Tamara Thomsen.

Figure 5. Dual CCR practice dives. Photo by William Gambrill.

Mosaic - WHOI, Wisconsin Historical Society. Photo by Tamara Thomsen.


Filming on USS Arizona*. Photo by Brett Seymour National Park Service.*


Evan Kovacs filming USS Lagarto*, Thailand. Photo by Richie Kohler.*

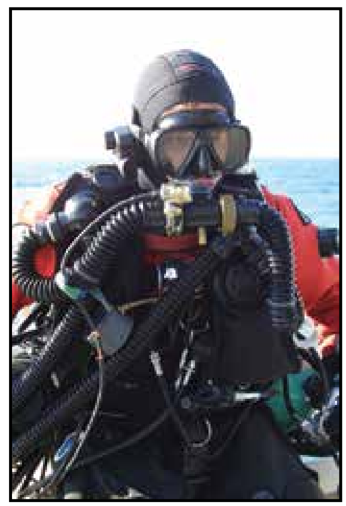

Evan Kovacs filming 3D coral at National Park in St John's. Photo by Brett Seymour.

Humpbacks in the Dominican Republic. Photo by WHOI, Becky Kagan.

Evan Kovacs filming humpbacks. Photo by Becky Kagan.

Filming Aggregate Plant at Lake Mead. Photo by WHOI, Becky Kagan.

Underwater standups at USS Arizona*. Photo by Brett Seymour, NPS.*



Evan Kovacs prebreathing a side-mount rebreather. Photo by Becky Kagan.

Humpbacks of the Dominican Republic. Photo by Becky Kagan.

Deep submersible Alvin. Photo by Evan Kovacs.

Camera and CCR for filming U869. Photo by Evan Kovacs.

CCR COMMUNITIES: RECREATIONAL

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There is not much of a recreational-diving community for rebreathers yet. The depth limit for recreational diving is traditionally about 130 ft (40 m) with no decompression and no significant penetration. In technical diving one can go much deeper, and even if the dives are shallow, they often involve a ceiling such as a wreck, cave, or decompression stop. I will argue that as long as you stay within the recreational envelope it is possible to design a rebreather program that is less demanding than a couse designed for technical diving because less knowledge and skills are needed to get out of trouble.

Figure 1. Depth limits for recreational and technical diving.

Some recreational divers want to use rebreathers. When we design a rebreather program for recreational divers, we must be aware of what they can and cannot reasonably be expected to do. Many rebreathers are not appropriate for recreational divers as the units have more capabilities than are needed, and designed for some environments (e.g., overhead) that are inappropriate, so the unit may be overly complex for the diver's needs.

The concept of a recreational rebreather course will work in relatively shallow water, typically not deeper than 100 ft (30 m) for no-decompression diving. This is a relatively simple, benign envelope where the large "gas reserves" of the atmosphere are not far away because direct ascent is always possible. The training requirements are significantly reduced if you have a sophisticated, simple machine that is safe to dive as long as there is a green "good-to-go" light in your face. If the light flashes red, the diver turns the mouthpiece valve from closed-circuit to open-circuit, aborts the dive, and surfaces.

There is more to a recreational rebreather course than that, of course, but aborting the dive to open-circuit is the most important skill needed when something goes wrong. This is an emergency procedure for a technical diver, too, but a technical diver may have a significant decompression obligation and need to remain underwater on open-circuit or stay on the rebreather loop in an emergency backup mode (e.g., semiclosed, manual O2 addition) so as to carry out effective decompression. Within the recreational rebreather envelope, this is not needed. By narrowing down the operational range, the scope of training is reduced.

Recreational divers typically do multiple dives in a day with extended periods — perhaps six months — between dive trips, and you cannot rely on them to have memorized a large body of complex skills that is instantly available. Recreational divers usually wish to extend their no-decompression time, which a rebreather does very effectively by raising the oxygen level above that of air with little risk of oxygen toxicity. Thus, training can focus on the vital skills.

Our approach in the Professional Association of Diving Instructors (PADI) is to require open-circuit training before enrolling in a closed-circuit course because the primary emergency skill when things go wrong is to switch to open-circuit and then surface. While that may occur in a stressful situation, the response is to return to a familiar operating procedure. After analyzing information on what people typically do wrong with rebreathers, we decided that the best way to manage problems and reduce task loading was through engineering the rebreather itself. The machine should look after the recreational diver by avoiding many of the foolish mistakes that he or she might make. Complexity should be built into the unit, not the operating procedures. A military or technical diver is expected to have a high degree of discipline and follow complex standard operating procedures — not so with the recreational diver.

Consider an automotive analogy. You can buy an inexpensive car with little automation, but more expensive cars have automatic transmissions, antilock braking systems, traction control, and automatic headlights. The simpler a car is to operate, the more complicated it is to build. The same philosophy holds for rebreathers; we are fortunate that several units of this nature are available, and others are in development. Let us call these recreational or Type R rebreathers.

What about the wider diving community? Divers conducting extreme technical dives will probably not be interested in our protocols, although some may be useful for any task-loaded diver. Since the recreational-diving community is larger than the technical community, this is good for manufacturers as they will sell more units and have more to spend on development of technical rebreathers. I believe that recreational rebreather diving is coming of age and will grow to the benefit of everyone.

Recreational divers cannot be expected to follow complex protocols as technical divers can. Photo by Karl Shreeves.

TECHNICAL-DIVING COMMUNITY

Phil Short
Independent Diving Instructor
Grand Cayman

I represent the technical-diving community as a consultant for manufacturers of closed-circuit equipment. Rebreathers are important to technical divers for exploring wrecks, caves, and mines, and to encounter marine life. Bottom times can be quite long for these activities and may require long ascent and decompression times. Rebreathers are excellent for these purposes as they minimize decompression time within the limits of safety while reducing logistics requirements.

Technical diving has grown much during the last 15-20 years. Dives in the 300- to 400-ft (90- to 120-m) range are now relatively routine because training and equipment have improved tremendously. During my first 200- to 300-ft (60- to 90-m) dives in the early 1990s, regulators would free-flow, and parts would fall off on almost every dive. The good news was that divers became adept at solving problems. Based on that experience, equipment has become much more reliable and training much better so problems are less common, but they still occasionally happen.

The big advantage of rebreathers is reducing logistics requirements. For example, we can run a project with the correct amount of open-circuit bailout gas but usually not use it, so multiple days of diving are possible with fewer expendables.

Figure 1. In Sala Mine (Sweden). Photo by Sami Paakkarinen (Divers of the Dark).

No dive should be driven by the cost of gas or equipment, but we all know that cost is a big factor. Some open-circuit dives we have heard about today have had incredibly high costs for helium, but rebreathers reduce these costs while increasing safety.

Technical divers have the same motivation as many recreational divers. We all wish to push into new realms such as virgin wrecks not visited by souvenir seekers or damaged by weather. Divers would like to penetrate deeper wrecks; without exhaled bubbles, gas is used more gradually so there is time to move slowly, deal with problems, and have good visibility for exit. The end result is increased exploration time and simpler logistics. Rebreathers are also advantageous for wall diving. An open-circuit diver would go to the planned depth, spend a short time, and ascend, but with the lower gas consumption of a rebreather, a diver can visit a wall in a leisurely fashion and slowly ascend while studying the marine life during a very efficient decompression profile.

Figure 2. Inside the Spiegel Grove *(Florida, USA). Photo by Brett Seymour (US NPS).*

Rebreathers are also useful in flooded mines, a man-made overhead environment. To penetrate the deeper galleries of a mine, an open-circuit dive would use a large amount of equipment and gas for each day of diving. With a rebreather, bailout gas can be staged but generally not used, so multiday projects are possible with no additional gas.

A unique characteristic of technical rebreather diving, particularly after wreck dives in the UK where I come from, is open-ocean decompression without a fixed reference. Because you drift during decompression, buoyancy must be controlled with absolute discipline and precision. Should something go wrong, bailout is complex with switches between numerous open-circuit gases to try to replicate a rebreather ascent; to prepare for this difficult process, training must be intense, with concentration on the basics.

Low work of breathing is critical as the technical diver often has to swim in a variety of positions. Diver propulsion vehicles reduce the need for swimming, but they can fail, so it is important to plan for worst-case scenarios. This is why cars are tested by driving into a concrete wall at 60 miles per hour and why rebreathers are tested independently under stressful conditions. Should something go wrong with your rebreather, an alarm system must inform you without the need to pick up a display, and most manufacturers now provide a heads-up display for this purpose. There must be multiple bailout options that allow you to stay on the loop without having to use your limited open-circuit back-up gas. If the loop is usable in one of its emergency back-up modes, it is always better to put your bailout gas into the rebreather.

Standardization within dive teams breeds familiarity to assist rescue. This applies across rebreather communities, and we can improve safety by learning from each other. For example, some technical rebreather training includes a rule of thumb called the three pre's: preassembly checks, predive checks, and prebreathe. These are like preflight checks that include a series of questions to make sure everything on the rebreather is working. Memory is not good enough. Checklists must be used either built into the software on the rebreather display or on a plastic sheet supplied by a manufacturer or training agency. Preassembly checks include such items as mushroom valves to ensure CO_2 cannot be rebreathed, gas supply and bailout cylinder contents, and absorbent canister content and packing.

Most important is a well-executed prebreathe to recheck the components after preassembly and predive. The rebreather is breathed for five minutes with the nose blocked, and the PO_2 display is carefully observed to ensure the oxygen or gas injection system is working and the setpoint is maintained. The prebreathe also checks for proper CO_2 removal. The experience of my friend who was cave diving in France illustrates prebreathe importance. The divers conducted their prebreathes sitting on the rocks in the grass outside the cave inlet. When one of the divers passed out and fell forward with the rebreather on his back, the other divers were able to revive him and discovered that his canister was in his house 20 miles (30 km) away. He had been so excited about the dive, he had neglected to insert his canister even though he completed his checklist. This human error was caught during the five-minute prebreathe. Without a prebreathe, he would have passed out a couple hundred meters into the cave and drowned.

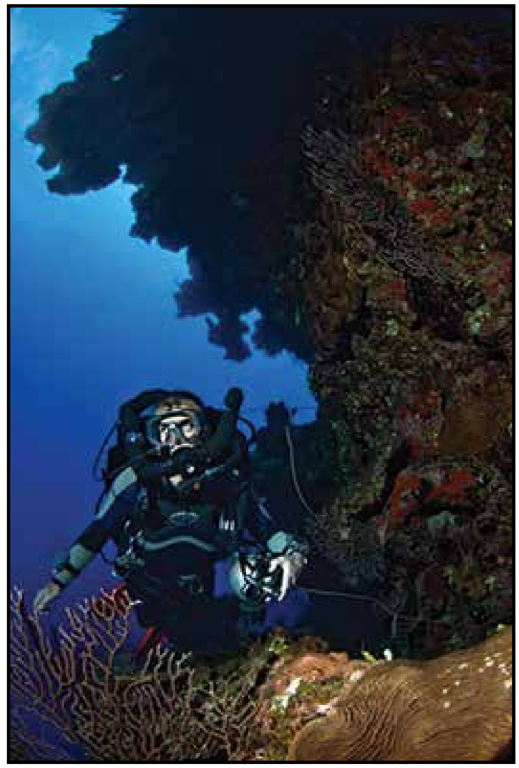

Figure 4. On the north shore wall (Grand Cayman). Photo by Kevin Gurr.

Figure 3. Phil Short on the Thistlegorm *wreck (Red Sea, Egypt). Photo by Leigh Bishop.*

Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3. AAUS/DAN/PADI: Durham, NC; 2014.

CAVE-DIVING COMMUNITY

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Caves are uniquely different from other diving environments. Divers leave the safety of the open water and go underground where there are no quick aborts and no bailouts. Everything has to be considered relative to the time away from the entrance. Penetration makes the difference, distance from the entrance is critical, and it all focuses on getting back to the entrance. No matter what happens, there is no cutting decompression time and relying on a recompression chamber in case you get decompression sickness (DCS). With a rebreather, your plan for dealing with problems such as bailout is entirely different from open-circuit scuba. Bailout gas and scrubber duration are the limiting factors for a rebreather, particularly for a dive of three to four hours against a current that is not uncommon and not trivial. How do we plan for and streamline this? How is the rebreather mounted, and how are the bailout bottles configured? The total package determines whether you can make the swim. The details matter.

Figure 1. CCR cave divers utilize DPV units to extend exploration. Appropriate gas planning, including staging bailout bottles, is critical for proper exiting in case of DPV or CCR failure. Photo by Pete Nawrocky.

At the first *aquaCORPS* conference, Dr. Bill Hamilton asked for definitions of a technical dive. Based on my unfortunate experiences in recovering 20 bodies from caves, I defined a technical dive as when you switch from one regulator to another to change gas mixes. That is when most fatalities occur, and that is why rebreather diving is so valuable — you never need to change gases because the breathing mix is automatically controlled independent of depth. One of the biggest pleasures of rebreather diving is never having to decide which regulator to put in my mouth after 120 minutes in the water. I just keep breathing. This is a common theme for cave divers who use rebreathers.

Another benefit of automatic mixture control with a rebreather is eliminating the worry about oxygen toxicity because the PO_2 remains essentially unchanged during both penetration and decompression on a deep dive that may last three to four hours. For long runs, cave divers are beginning to use oxygen setpoints as low as 1.0–1.2 atm. You can forget everything you learned about oxygen toxicity units (OTU) because you will never hit the OTU maximum.

Figure 2. Lamar Hires enters a cave system using an Optima CCR and bailout bottles carried sidemount style. Photo by Pete Nawrocky.

Cave-diving rebreather courses are largely about emergency procedures because returning to the exit is your only option, since aborting the dive is impossible. If you have pushed yourself far back into a cave and still have a two-hour transit to the exit, stay on the loop if at all possible, and save your bailout gas in case the loop fails. Methods for staying on a loop when the automatic oxygen-addition system has failed include flying manually by watching your PO_2 readouts and adding oxygen manually or in semiclosed mode by exhaling every third breath through your nose.

Rebreathers allow long decompression dives that would be practically impossible with open-circuit where not enough bailout gas could be carried. But how much bailout gas is enough for a rebreather diver, and how should the problem of mixed rebreather and open-circuit teams be managed? This is controversial, and there are three methods to consider: team, self-sufficiency, and staged. We favor the team-management approach where rebreather and open-circuit divers are considered mutually dependent buddies.

Rebreather bailout gas requirements are based on open-circuit experience, distance from the cave entrance, and redundancy. An open-circuit diver who enters a cave with a set of 104s pumped to normal cave pressures would have approximately 320 cu ft of gas, of which two-thirds would be reserved for exit. Where a single aluminum tank with 80 cu ft might be

Figure 3. Entrance to the Little River cave system. Photo by Pete Nawrocky.

sufficient for an open-water dive, a cave diver would carry two aluminum 40s with separate regulators for redundant self-sufficiency. Cave-diving teams apply the same rule and carry multiple bottles to make gas sharing easy. You hand off a full bottle and assume it is empty when you get it back. That way there is no chance you will use an empty bottle when you are an hour away from the entrance. With two bottles, you can choose to give one away or to outswim the person who is asking for it — and this can be a real choice.

Staged bailout is usually used for longer penetrations on a scooter where you may be 0.5-1.5 miles (0.8-2.4 km) from the entrance. Because you do not have to swim with a scooter, your oxygen consumption is only about 0.5 L·min^{-1}, which lowers your total gas consumption. In theory you could carry less bailout gas, but what if the scooter failed? On a 2,000-ft (610-m) penetration where 80 cu ft might be adequate, you still plan your bailout requirements for a swimming penetration, and three to four bailout bottles would not be uncommon. The diver might leave two 80s closer to the entrance and save two 40s for when he gets off the scooter to swim.

Mixed teams of rebreather and open-circuit divers are an issue because emergency procedures are different, and planning must ensure there is enough bailout gas for an open-circuit diver. An open-circuit diver typically carries a bailout regulator on a long hose that can be passed to a buddy who needs gas. A rebreather diver does not use a regulator with a long hose, so he would give the open-circuit diver a bottle, but this may be less gas than the open-circuit diver needs. Thus, an open-circuit diver in a mixed team should carry an extra bailout bottle because unless the team has three or four people, a single rebreather diver will not have enough bailout gas to support the open-circuit diver.

The rule of thumb in cave diving is to have 1.5 times the gas needed to get the diver out. If each diver in a three-person team carries 80 cu ft, there is plenty of gas; but in a two-person team there is only enough gas to get one diver out, and the other diver is left with about 30 cu ft. For a single diver, this minimal approach leaves no reserves and no one to help. I see a lot of dives where there is no planning for bailout gas to get everyone back to the exit. It is not satisfactory for the open-circuit divers to use doubles while the rebreather divers carry a single bailout bottle.

Figure 4. Bailout and a CCR are staged along the cave line. In case of light failure, divers can navigate out and find extra equipment placed for contingencies. Photo by Pete Nawrocky.

Communications are very important for mixed teams. Your open-circuit buddy needs to know the meaning of flashing LEDs on your rebreather so he can help if there is a problem. And he needs to know that if you switch from your rebreather loop to open-circuit, you aborted the dive because your rebreather has failed.

Cave exploration that pushes beyond the bounds of what is already known is another challenge. Often these are low caves where side-mounted bottles are the only possible configuration. This is fine for open-circuit, where all we had to do was put a long hose on one cylinder, but rebreather divers, such as Dr. Harry Harris in Australia, are building their own sidemount rebreathers. For the most part, no one is going to stop you from being your own crash-test dummy in a Florida cave, but with individual sidemount rebreather configurations, planning emergency procedures within teams is more difficult.

Other issues regarding cave diving with rebreathers need consideration. Can we find a better way to monitor rebreather operation in low or zero visibility than just listening for the steady rhythm of the oxygen solenoid? Can rebreathers be an alternative to open-circuit backup gas for bailout?

PUBLIC DISCUSSION

MARTIN ROBSON: Earlier today, Michael Menduno said checklists and full-face masks were viewed as important at Rebreather Forum 2.0 (RF2). Almost everyone now understands that checklists are essential, but what about full-face masks? Would each panelist please address the use of full-face masks with rebreathers?

MARK CANEY: For recreational divers, the available full-face masks are probably not appropriate. The disadvantages outweigh the advantages. In the event of a problem, a recreational diver wants to remove his or her mouthpiece and get

Figure 5. Little Devils Basin. Photo by Pete Nawrocky.

gas from somebody else. Perhaps a mouthpiece-retaining strap might be helpful to avoid loss of the mouthpiece in the event that a seizure, etc., causes unconsciousness. I would like to see some research into whether retaining straps would be beneficial.

CHRISTIAN McDONALD: Some of our organizational members use full-face masks, but I cannot speak from experience.

LAMAR HIRES: I do not like full-face masks, and I do not know many people who use them in the cave-diving community. Only a couple of full-face masks I know of are properly fitted for rebreathers. Mainly, they are for television, not actual use.

EVAN KOVACS: The film community uses full-face masks quite a bit, largely for communications. After watching several people have seizures and subsequent problems, I am a very big fan of the full-face masks. I do not wear one on every dive, but our entire team uses them on most deep dives.

MICHAEL RUNKLE: The Navy uses full-face masks for most of our missions with the MK-16 and Viper. The MK-25 (closed-circuit oxygen) uses a retention strap, not a full-face mask, because of the unique nature of the missions.

PHIL SHORT: Full-face masks have advantages, such as communications. The loss of the mouthpiece in a rebreather is particularly dangerous since gas in the counterlungs that provides buoyancy is also lost. This does not happen with open-circuit. For technical diving, a head strap that holds the mouthpiece in position might be useful to prevent drowning. Many full-face masks increase the CO_2 deadspace within the mask, but full-face masks with an internal mouthbit and a nose clip prevent this.

Figure 6. Proper rigging of bailout bottles is critical, which reduces the diver's profile versus flow and keeps bailout easily accessible. Photo by Pete Nawrocky.

REBREATHERS: OVERCOMING OBSTACLES IN EXPLORATION

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ABSTRACT

Rebreathers have been utilized by civilian, noncommercial divers for more than 60 years to explore and study shipwrecks, reefs, and flooded caves. In recent times as the more readily accessible sites have been cherry picked, explorers have turned to more remote, deep or distant sites to make new discoveries. Rebreather technology has made sites that would be logistically very difficult to explore on open-circuit scuba far more accessible. This presentation looks at the current state of the use of rebreathers in exploration. The current envelopes of time, depth, and distance, and the limitations to further extending these parameters are described. Some issues such as bailout strategies for extreme dives are considered, and the possible role of full-face masks in "drownproofing" rebreather divers is discussed.

Keywords: bailout, exploration, full-face mask, segmented staged decompression

INTRODUCTION

The first successful "technical" rebreather cave exploration probably occurred in Keld Head in England in 1945 (Farr, 1991). Unfortunately this was soon followed by the first recreational rebreather death in Wookey Hole in 1949. However, the advantages of having a free-swimming diver able to move through the multiple sumps of Wookey were immediately obvious, especially compared with the cumbersome tethered standard dress that had been used up to that point.

Moving ahead to more modern times, that same logic still applies, and the modern free-swimming explorer has made extraordinary incursions into caves, onto wrecks and down reef walls to describe and study these unique environments. The further from the surface the diver travels (whether horizontally into a cave or into the depths), the more the advantages of rebreathers begin to outweigh those of open-circuit (OC) scuba. Essentially, a closed-circuit rebreather (CCR) has close to the same duration at depth as it does at the surface. With rebreather durations of 10 hours in some units, this allows great depths and long penetrations to be made without the need to carry enormous amounts of open-circuit gas. This has important implications for diving in remote destinations where transporting large numbers of cylinders and gas supplies may not be possible. It also has important safety implications when diving at depth or in the overhead environment, where the pressure of time that comes with a finite gas supply can make problem resolution a great deal more stressful.

HISTORY

One of the first major technical-diving expeditions to draw attention to the benefits of CCR was the 1994 San Agustin sump dive performed by Dr. Bill Stone's expedition to Mexico's Huautla Plateau. Several of the newly designed Cis Lunar Mk 4 fully redundant CCRs were taken 4,439 ft (1,353 m) vertically down the dry cave 4 miles (7 km) from the entrance to explore the 100 feet of freshwater (ffw) (30 meters of freshwater [mfw]) — deep sump for a linear distance of 1,969 ft (600 m). To transport sufficient OC cylinders and gas to the sump had become an impossible quest. In fact the dives on this expedition consumed only 1,400 L of oxygen and 2,500 L of heliox in total (less than two full standard scuba cylinders).

Following the successful use of the Cis Lunar in Mexico, Dr. Richard Pyle (an ichthyologist from the Bishop Museum, Hawaii) began using the unit to capture new species of fish from the "twilight zone" region of the coral reef at depths of 197-492 fsw (60-150 msw) that had thus far been little studied. The number of new species found in this zone was staggering (Pyle, 1999), and this continues to be the case to the present day.

Both Stone and Pyle published their achievements, and soon the possibilities of CCR diving became apparent to more mainstream technical divers (Stone et al., 2002). In the last 10 years there has been an enormous amount accomplished on rebreathers including the following extreme examples (from personal communications and Internet sources):

- CCR cave — 886 ffw (270 mfw) at altitude, CCR, shotline, reeled out along debris cone (D Shaw, 2004)
- CCR shotline ocean — 928 fsw (283 msw), dual CCR (Krzysztof Starnawski, 2011)
- Longest cave traverse — Turner-Wakulla, 36,926 ft (11,255 m), passive semiclosed rebreather (pSCR), 7+15 h decompression, 295 ft (90 m) max depth (C McKinlay, J Jablonski, 2007)
- Longest CCR sump — Pozo Azul, 16,929 ft (5,160 m) (J Mallison, R Stanton, J Volanthen, R Houben, 2009)
- Deepest sump passed to air — Notre Dame des Anges in Vaucluse, France, 328 ft (100 m) depth (Syvain Redoutay, 2003)

- CCR wreck — *Milano*, 774 ft (236 m) (van der Horst, Scuotto, Marconi, 2008)

Over the past 10 years the author and his companions have been extending their personal limits while developing techniques and equipment for exploration, primarily in cave diving.

The year 2006 saw a six-man team led by Paul Hosie explore a remote sinkhole in the Kimberley Ranges in the north of Western Australia known as Kija Blue. This very isolated site was many hours drive from the nearest town, and access required a 20-minute helicopter ride from a small settlement. In a 10-day period, the team performed more than 60 dives to a maximum depth of 364 ft (111 m) and up to 7.5 hours duration. The cave was mapped and imaged without significant incident. Using open-circuit for this expedition would have added immensely to cost of the trip, primarily in helicopter and gas expenses.

In 2008 diver Craig Challen and the author successfully added approximately 394 ft (120 m) of line to the end of Cocklebiddy Cave on the Australian Nullarbor Plain. The cave is more than 3.7 miles (6 km) long, divided into three sumps with large rock collapse chambers separating them. The traditional approach to exploration in this site has been with large teams of divers carrying dozens of scuba cylinders through the cave using submersible "sledges." Challen and the author used a lightweight technique with long-range rebreathers and dive propulsion vehicles modified with homemade lithium ion batteries for extra range. With support from just six other divers, they proceeded to the end of the cave and back in less than 20 hours total. Challen dived the final section of the cave past a sidemount restriction solo, while the author awaited his return and "babysat" Challen's CCR. The last 394 ft (120 m) were dived using a "no-mount" system developed by Challen specifically for this dive. "No-mount" or "off-mount" diving systems involve open-circuit or rebreather-based units that can be completely removed and then pushed ahead of the diver to negotiate very restrictive passages.

The third cave of interest to be explored by the author and his teammates is the Pearse resurgence in New Zealand. A Vauclusian spring at an elevation of 899 ft (274 m), the resurgence lies in a steep-sided valley 2.5 hours walk from the nearest vehicle access point. Helicopters carrying equipment in cargo nets were used to transport all diving and living equipment to the site for the two- to three-week encampments. The author first visited the site in 2007, and since then the team has pushed the cave from 410 ffw (125 mfw) to 725 ffw (221 mfw) in depth. With the slight flow in the cave, a water temperature of 44°F (6.5°C) and the great depths, diving presents numerous physiological and logistical obstacles to safe exploration.

The primary issues that have been overcome include thermal protection for dives lasting up to 17 hours total, with up to 7.5 hours in the water; dive and decompression planning for solo exploration dives; and managing the theoretical risk of respiratory failure and CO_2 buildup at extreme depths.

Figure 1. The stunning clarity in entrance lake of the remote Kija Blue sinkhole, Western Australia. Such remote locations are very difficult to explore without the logistical advantages offered by rebreathers. Photo by Richard Harris.

THERMAL PROTECTION

Over the course of five such expeditions to New Zealand and other trips diving cold-water caves in Tasmania, the following strategies have been developed to combat hypothermia in these exposures. Heavyweight compressed neoprene drysuits are worn. The suits have built-in boots, which allow air to circulate around the foot (c.f., the "Rock Boot" style, which squeezes any insulating air out of the area). Undergarments are comprised of a wicking layer next to the skin, a 12 V heated layer and then a 400 g Thinsulate® full-length garment over this. One manufacturer can provide the heating wires within the Thinsulate, which has been used with good effect. Twelve-volt heated glove liners under the diver's drygloves and heated foot soles are also used. Power comes from 20 Ah battery packs carried by the diver for the deep part of the dive, and then surface-supplied power is adopted from 130 ffw (40 mfw) upward.

The second essential component of the thermal strategy is the use of dry decompression habitats in the cave. These 1.0 cubic meter plastic containers are secured at 131, 92, 52 and 23 ffw (40, 28, 16 and 7 mfw) (the odd depths are due to the topography of the cave) and provide a dry refuge for decompression without active heating. Small homebuilt CCR and oxygen rebreathers are used in these habitats, which have the advantages of low gas use, warm and humid breathing gas, and low noise (an important feature when sitting for many hours in a plastic bucket!). Various communications devices allow the diver to contact the surface, and a schedule of support diver visits who bring warm victuals assist with diver comfort and safety. Once in the habitats, we have found little concern with keeping the diver warm — an important point for efficient decompression.

DIVE AND DECOMPRESSION PLANNING

Decompression planning information for recreational dives beyond 492 ffw (150 mfw) can be described as scant at best. However, by keeping the divers warm and well hydrated during the decompression phase, and with the possible decompression advantage conferred by the dry habitat environment (Mollerlokken et al., 2011), the team has not suffered any decompression incidents in 16 person-dives between 492-725 ffw (150-221 mfw). Furthermore, the divers almost without exception have felt extremely well after the dives, not developing the minor symptoms that are often attributed to subclinical decompression illness. This compares favorably with an incident rate of 13.3-45.5 percent (95 percent CI) in the 295- to 404-ft (90- to 123-m) range (Doolette, 2004), which fits with the team's own experience at these depths where all decompression is done in water. By performing prolonged stops at the four habitat depths, the overall runtime of the dive is prolonged. Because the diver stops at the habitat depths rather than following the decompression ceiling as it ascends, offgassing is not proceeding as efficiently as it might. The author has coined the term "segmented staged decompression" for this approach. The significant advantages are thermal comfort, possible improved decompression efficiency in the dry environment, decreased risk of central nervous system oxygen toxicity (with less likelihood of drowning if it did occur), ability to maintain hydration and caloric balance, and ability to communicate with the surface. Although the overall dive time is prolonged, this has proven quite tolerable for decompressing divers due to improved comfort and support.

Figure 2. Cave diver Sandy Varin, in the entrance to the Pearse resurgence in NZ, wears a twin rebreather system built by combining a backmounted rEVO unit with a Classic Inspiration scrubber and circuit attached to the diver's left side. Photo by Richard Harris.

RESPIRATORY FAILURE AND CO_2 RETENTION AT DEPTH

Mitchell et al. (2007) reported on a fatality that occurred during an extreme technical cave dive in South Africa. The diver succumbed to CO_2 poisoning as a result of a dramatic rise in work of breathing, secondary to the high gas density being respired at a depth of 866 ffw (264 mfw). This represented a failure in the respiratory mechanics of the diver himself rather than an equipment issue per se. However, the use of a CCR in such a deep dive probably contributed to the death due to the resistance inherent in such equipment compared with open-circuit systems. The other issue was arguably an imperfect diluent selection, which due to the high nitrogen content added significantly to gas density at depth (an equivalent air depth density of 230 ffw [70 mfw]). This unfortunate fatality has given enormous insight into the hazards faced by deep CCR divers, but strategies to overcome or eliminate this problem are currently lacking.

As a diver descends, especially past approximately 492 ffw (150 mfw) depth, the increase in gas density (even with an appropriate heliox mixture) begins to manifest as a subjective increase in work of breathing. This is especially noticeable with increasing levels of exertion and hence rising inspiratory and expiratory flow rates in the diver's airways. With increasing gas density comes increased resistance in airways, especially as gas flow moves from laminar to turbulent. Greater resistance requires greater differential pressures to maintain the same gas flow in the lungs, especially during exhalation. Eventually the intrathoracic pressures become so high that small airways begin to occlude before the diver has fully exhaled. To make up for this shortfall in ventilation, the diver responds by breathing with more force and often in a rapid and shallow fashion. This is the beginning of a vicious cycle that will result in fatal CO_2 retention unless the cycle can be rapidly interrupted. (See Mitchell, "Rebreather Physiology" in Rebreather Forum 3.0 [RF3] for a detailed discussion of this problem.)

Figure 3. Australian cave diver John Dalla-Zuanna explores a subterranean passage at a depth of 60 mfw. On his sides are open-circuit bailout cylinders that can be used in the event of a rebreather failure. Photo by Richard Harris.

Preventative strategies include avoiding such depths, using the lowest density breathing gas possible, avoiding exertion, and maintaining a slow, deep, even respiratory pattern at all times. In the event that the cycle begins, the diver must immediately ascend to a safe depth, minimize exertion, and consider changing to open-circuit, which will have a lower equipment resistance. It is possible that rebreathers with front-mounted counterlungs may provide some splinting effect on the airways due to the positive static lung load they offer. Conversely, a back-mounted counterlung (such as on the Mk 15.5 CCR used by David Shaw) may have an adverse effect on respiratory mechanics. The important lesson here is that the diver must both understand what is happening and be alert to the earliest signs arising. While our team has not overcome this issue, we have seen the early symptoms and on one occasion aborted a dive before the diver was incapacitated.

Figure 4. A close up of Sandy's twin unit, the "R2D2." The extra cylinder on the right-hand side is for drysuit inflation. Photo by Richard Harris.

Two more issues are relevant: bailout strategies for deep CCR diving and the role of full-face masks (FFMs) in technical CCR diving.

DEEP BAILOUT STRATEGIES

A rebreather may malfunction at any depth, and it is standard practice for non-military rebreather divers to carry sufficient open-circuit bailout gas with which to complete the dive and return safely to the surface. Although a catastrophic rebreather failure is an uncommon event, it does happen, and hence a contingency plan must be in place. For most technical divers, the bailout plan is either sufficient open-circuit gas to complete the dive or a second bailout rebreather carried with them.

A rebreather may malfunction in a variety of ways, and not all failures are incompatible with completing the dive by "staying on the loop" in some form. However, some failure modes are not recoverable, and so bailing out to another source of respirable gas must occur. The idea of a bailout rebreather is especially attractive on very long cave penetrations or very deep dives where it may be difficult to carry, share, or stage enough OC gas for a team member to return to the surface. On some deep wreck dives, for example, the risk of missing the shotline at the end of the dive is unacceptably high, so gas staged on the upline or decompression station cannot be relied upon.

However, there are some occasions when it may not be acceptable to bailout onto a second rebreather. Such an occasion exists in the case of CO_2 retention due to effort-independent respiratory failure, as described above. In this setting the primary rebreather is not at fault; rather, the problem arises within the diver as a function of depth, gas density, exertion, etc. Transferring to a second rebreather would not break this vicious cycle. The following table considers the likelihood of certain rebreather failure modes and the requirement for bailout. It also describes whether, in the author's opinion, such a bailout would be successful. We used such a decision matrix in our bailout planning for very deep dives in the Pearse Resurgence.

Bailout rebreathers have a number of advantages over OC gas, including:

- There's no need to change decompression planning or adjust the schedule.
- They have "unlimited" duration in an emergency.
- With a twin bailout valve (BOV), they can be activated with the flick of a switch.

However, they do have disadvantages:

- They need to be checked throughout the dive to ensure they are available for use in an emergency (i.e., not flooded, full of a breathable gas).
- The complexity of the system leads to a high degree of task loading during the dive and hence requires a lot of practice on smaller dives first.
- There is added expense.

Open-circuit bailout for very deep dives has the very obvious disadvantage that gas is consumed at an alarming rate at such depths. A rebreather failure (or indeed a diver with respiratory failure) deep on a wreck or in a cave is likely to

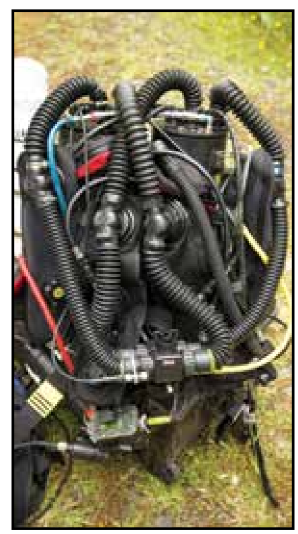

Figure 5. For deep dives in the Pearse Resurgence, Craig Challen uses a Twin Megalodon rebreather, with the two loops accessible by a custom-made dual bailout valve. This allows the diver to change from one loop to another with the flick of a switch. Photo by Richard Harris.

promote a high respiratory minute volume (RMV), and so the duration of a cylinder of gas will be measured in minutes. It is unlikely that the diver will be able to carry sufficient gas to safely return to a staged cache of gas.

Table 1. Decision matrix for bailout strategies in deep, cold-water CCR dives. The left column lists the possible failure modes of closed-circuit rebreathers used in deep technical diving. The likelihood of such a failure is assigned a probability of low or moderate. If such a failure occurred, the requirement to bailout from the primary rebreather onto another source of respirable gas is either mandatory (the primary rebreather cannot be breathed) or not mandatory (the primary rebreather may offer other options to solve the problem — e.g., changing to semiclosed mode). If the diver bails out to another rebreather (a bailout breather [BOB]), the final column describes whether, in the author's opinion, the changeover will be successful in allowing the diver to successfully end the dive and safely return to the surface.

Problem	Likelihood	Bailout mandatory	BOB successful
FLOOD	LOW	YES	YES
ELECTRONICS	LOW	NO	YES
GAS SUPPLY e.g. O2 spike	LOW	NO	YES
CO2 due to scrubber/loop problem	MODERATE	YES	MAYBE
Respiratory insufficiency	MODERATE	YES	NO

FFMs IN REBREATHER DIVING

During RF3 it was suggested that perhaps 80 percent of rebreather fatalities have the final common pathway of drowning as the cause of death (COD) (see Fock, "Killing Them Softly" in RF3 for details). We know that listing drowning as a COD is unhelpful from the point of view of understanding why divers die, because incapacitation for any reason underwater will result in drowning if the ability to protect the airway from the ingress of water is lost. But can we devise a strategy to prevent drowning when a diver loses consciousness? Two devices are often proposed to help protect the airway of an unconscious rebreather diver and thus increase the time in which a successful rescue may be performed by another diver or surface observer. The first is a gag strap — a simple rubber strap that goes around the diver's head and holds the mouthpiece in the diver's mouth. This unquestionably reduces jaw fatigue, but there is some dispute as to the effectiveness in protecting the airway of an unconscious diver. The second is an FFM, which has an excellent safety record in military applications and has been shown to be effective in drownproofing divers who have an oxygen seizure and are rescued relatively quickly. With this in mind, many technical rebreather divers (including our team) have dived a variety of models of FFMs but have reluctantly moved away from their use because of the additional problems that they generate.

The following issues have been identified with FFMs in this sphere of diving:

- There is increased difficulty of bailing out from the primary rebreather. In the event of a bailout to open-circuit, the CCR diver on FFM must either remove the FFM and replace it with a standard mask and deploy a second-stage regulator from a scuba cylinder, or they must use a BOV, which can be switched to OC mode. In the latter case, the supply gas should be a large offboard gas supply to give the diver plenty of time to prepare for moving to the next cylinder. At that point, the diver has two options: Remove the FFM as per the first example, or connect into the next gas cylinder and continue to use the FFM and BOV. Staying with the FFM requires the use of a quick-disconnect system (which must not be fumbled during the changeover!) or a switching block, the use of which carries its own hazards, especially when different decompression gases are in use.
- The two FFMs most commonly used are the Draeger Panorama and the Kirby-Morgan M48. Both have an oral mouthpiece, which the diver uses like a standard second-stage mouthpiece (oronasal masks carry too high a risk of flooding the loop or CO_2 retention due to increased deadspace). The Panorama offers excellent vision and is comfortable to wear, although the author has found it prone to leakage. It uses a Draeger P-Port connection to attach the BOV or DSV.
- This mask is effective but can be difficult for the diver to use especially when wearing drygloves (i.e., it can be hard to mate the DSV male portion with the mask by feel). If the diver plans to insert another second-stage regulator into this underwater, the second stage must be fitted with a male P-port instead of a mouthpiece, and again the changeover must not be fumbled.
- Kirby-Morgan has approached this problem in a different way by providing a tear-away pod on the lower half of the mask. In the event of the diver bailing out, the pod can be removed and replaced with another pod or a second-stage regulator inserted directly into the diver's mouth. The pod can be difficult for the diver in drygloves to operate, and the upper mask portion itself provides very restricted vision to the diver.
- A minor concern with both masks is there is no way to

open the mask to air when on the surface with the DSV connected. When hypoxic diluents are used for deep diving, there is a risk of hypoxia in the diver before the dive commences. Our team has suffered one incident caused by this problem.

- Technical divers do not undergo the rigorous training that military divers do, nor do they generally follow the same strict operating procedures. Diver supervision is less thorough, and solo diving is more likely. There is a far greater learning curve for the use of FFMs, and they require many hours of practice before they feel as safe and comfortable as a standard mask.
- On dives of extreme depth or penetration, it may be a moot point whether the airway is protected during a loss of consciousness if the diver is so far from the surface as to make rescue impossible. This is essentially the case in many technical dives.

Despite these operational concerns with FFMs in rebreather diving, the potential to save lives is clear, and this is an area where both manufacturers and training organizations could work further. Trainers and manufacturers might consider more extensive testing of FFMs to determine which models and bailout systems are effective in recreational rebreather diving. Early introduction of FFMs in the class setting to provide correct instruction in the use of FFMs could prove lifesaving.

SUMMARY

Rebreathers have enabled the exploration of the underwater world to move to a new level. Remote, deep, and long penetrations all especially benefit from the use of this technology. As we push deeper, however, we are encountering a new list of problems to solve — in particular that of carbon-dioxide retention. It seems that the current "safe" operational limit of closed-circuit rebreathers is in the 492-656 ft (150-200 m) range, beyond which the likelihood of fatal respiratory failure may be unacceptably high. Bailout strategies during deep rebreather dives need to be carefully considered, and the use of a second rebreather may not be a perfect solution. Finally, the use of FFMs as a viable tool to save lives in recreational and technical rebreather diving has pros and cons that needs to be further explored by all involved in this style of diving.

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REBREATHER EDUCATION AND SAFETY ASSOCIATION (RESA)

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By show of hands, about 90 percent of Rebreather Forum 3 (RF3) attendees were rebreather divers, and none believed that the current safety record is acceptable. That is why the Rebreather Education and Safety Association (RESA) was formed.

Our first discussions about forming RESA were in 2010 at the Beneath the Sea show, where several manufacturers found many points of agreement despite being competitors. This led to further meetings during which we decided that if the industry were to grow, an organization was needed that would allow us to solve common problems (not design the perfect rebreather). The Professional Association of Diving Instructors (PADI) supported the idea by lending us a room at the 2010 Diving Equipment and Marketing Association (DEMA) event, and attendance was wide.

A bylaws committee was formed to decide what RESA was going to be, defining its mission and values. After lots of discussion and by consensus, we decided the mission would be to improve the worldwide safety and education of rebreather diving, promote the use of quality-assurance standards, and improve development.

We organized as a nonprofit industry group with a very small budget from member dues and filed with the Internal Revenue Service (IRS) for nonprofit status. By February 2011, we had elected officers from member companies, with Kim Mikusch of Jetsam as president, Paul Raymaekers of rEvo as vice president, and Bruce Partridge from Shearwater as secretary. There are two membership categories: regular and associate. Requirements for regular membership include: a) be an active manufacturer of rebreathers; b) have an existing installed base of units in the field; c) have a documented quality-assurance (QA) system that is audited by a third party; and d) conduct third-party testing to a recognized standard. Charter regular members include Ambient Pressure Diving, Innerspace Systems, Jetsam, Poseidon, rEvo, VR Technology, and Shearwater. Shearwater was included as an exception because they make electronics for several rebreathers, and Partridge was very active during the formation of RESA.

Associate members are individuals or firms engaged in rebreather operations that are beneficial to the industry. This includes manufacturers who meet some but not all the requirements for regular membership and are working toward them, such as acquiring certification by the International Organization for Standardization (ISO). Training agencies are also considered for associate membership. Training agencies and manufacturers must cooperate as each group seeks to resolve its own issues. Training agencies with associate member status presently include the International Association for Nitrox and Technical Divers (IANTD), International Association of Rebreather Trainers (IART), the Professional Scuba Association International (PSAI), Silent Diving, and Technical Diving International (TDI).

Members are from around the world in different time zones and meet face-to-face about twice a year. We also have member forums, but everything else is done by email.

The standards that members can choose to observe include the European Union (CE mark), U.S. Navy, and National Oceanic and Atmospheric Administration (NOAA). Standards provide a basis for testing and quality assurance in areas such as work of breathing (WOB) and scrubber duration. The CE mark is probably the best known and most widely used standard. The NOAA standard is based in part on the U.S. Navy standard.

RESA is open to inviting guests such as Simon Mitchell to help with technical areas that will improve safety. Particular targets for work are:

- *Checklists.* Predive and postdive equipment checklists are essential for every rebreather model. The first thing a diver should see when he or she opens a rebreather box is a sticker warning that the checklists must be used. Stickers must be consistent across all manufacturers.
- *Manufacturer/training agency cooperation.* Manufacturers must get timely information about their units to training agencies and work with the agencies to develop minimum training standards.
- *Data logging.* There is precedent for this at the National Transportation Safety Board (NTSB), and the rebreather industry should take notice. Many rebreathers already have black boxes, and those that do not will probably have them soon. Training agencies need assistance from manufacturers in downloading the black boxes, and manufacturers should be involved in accident investigations without touching the equipment.
- *Rebreather accident investigation.* One of the biggest problems is insufficient high-quality information about accidents. All RESA manufacturers will provide protocols for first responders and the U.S. Coast Guard to use in accident investigations.

- *Change thinking and culture.* There are a lot of great instructors and great divers, but a typical profile for a rebreather fatality is an older, experienced diver or instructor, and the triggering event is something that should not have happened. How do we to stop that? There is pretty good agreement that training can be rigorous, and new, well-trained divers don't seem to be likely to die, but training is of no value if the divers don't observe it. Our job is to work with the training agencies, instructors, and others in the industry to change the thinking and culture.

PUBLIC DISCUSSION

UNIDENTIFIED SPEAKER: A lot of diving equipment and information is already out there. What is RESA going to do to address that?

JERRY WHATLEY: Excellent question, and it's a huge problem. Manufacturers see initial purchases but not necessarily secondary purchases. Usually the first rebreather you buy is not your last, and ANDI, TDI, and IANTD gave an excellent presentation indicating there have been 30,000 certifications since 1990. There are a lot of used rebreathers and a big secondary market. The solution is continuing education and divers who refuse to dive with a diver who does not use a checklist or prebreathe. It's just like being on a jet and seeing a drunken pilot enter the cockpit — you are going to say or do something. We have all known of people who have been lost in rebreather accidents. There is no reason for this.

UNIDENTIFIED SPEAKER: How is RESA going address the resale of used rebreathers?

JERRY WHATLEY: It's a huge problem as there are lots of rebreathers in the community. Usually, the first rebreather you buy is not your last, and there is a big secondary market for used units. The new generation of divers who buy these units needs to be educated. Some of that education may have to take place at the dive site. If an experienced rebreather diver sees a new diver setting up a unit without a checklist or prebreathe, the experienced diver needs to point this out and, if needed, refuse to dive with that diver. If you are on a jet and see a drunk pilot, you are going to say and do something rather than continue on that flight. We all have friends who have been lost in rebreather accidents. We have to take on the responsibility to stop this from happening ourselves.

CCR Wreck Diving. Photo Howard Ehrenburg.

BUSINESS PANEL

Mark Caney, PADI (Chair)
Bruce Partridge, Shearwater Research
Chauncey Chapman, Hollis
David Concannon, David G. Concannon, LLC
Nancy Easterbrook, Divetech
Paul Toomer, Diving Matrix
Tom McKenna, Micropore

Q: How important will rebreathers be to the diving industry over the next five years?
A: They will become very significant, especially units aimed at recreational divers. This technology represents a whole new growth area for the diving industry, however, it must be properly managed to achieve maximum safety.

Q: How important or viable is the standardization of consumables between manufacturers of rebreathers?
A: If this technology is to achieve its potential it is essential that as many consumables are standardized as possible. This is particularly the case for the diving-travel industry.

Q: Will recreational divers use rebreathers, or are they just tools for technical divers?
A: There will be a distinct and significant sector for recreational divers. They will need specific training, educational and operational considerations.

Q: What should the relationship be like between manufacturers of rebreathers and training agencies?
A: A close relationship is very desirable as the technology is still evolving. Many manufacturers want to play a role in the screening or training of instructors and need to provide information on unit-specific protocols to training organizations.

Q: Some modern rebreathers have extremely sophisticated capabilities. Do we need to change the way we train divers and organize dives as a result?
A: Yes, training needs to be designed to ensure the divers can make appropriate use of the new technologies. Such sophistication can also be used to make units easier to operate.

Q: Can you teach someone to use a rebreather without prior open-circuit experience?
A: The general consensus was that it is possible. An SSI delegate said that they are doing this now, a PADI delegate said that they require open-circuit experience at this point in time but believes that direct entry into rebreather training could be possible if the training was appropriately designed.

Q: Does a retailer have liability concerns when selling rebreather-related consumables (e.g., O_2 sensors) if the consumer does not know how to use them properly?
A: In the USA, at least, the retailer can always be sued.

Q: Is there a concern that various agencies issue different level of competencies (such as depth limits) for different diver grades?
A: Ideally there will be some convergence of levels in the future, but the present system works as long as the training agencies make it clear what the competences of each level of diver are.

Q: What can be done to stop someone buying a second-hand CCR on eBay and diving with it?
A: Probably someone will always be able to buy a unit in this way. Service providers can look for proof of competency before offering supporting services such as dive trips or cylinder fills however.

Q: Are instrument-led or automatic self-checking rebreathers better than models that require the diver to perform a manual checklist?
A: There are some advantages to such systems especially for recreational divers. A good checklist can also be effective but it must be consistently followed.

Q: The CE marking/testing of rebreathers in Europe (EN14143) seems to work well. Could this standard be used in the USA?
A: Ideally a standard will evolve that non-European countries can have input to as well. EN14143 could become a basis for this, at least in part.

TRAVEL PANEL

Nancy Easterbrook, Divetech (Chair)
Mark Caney, PADI
Kevin Gurr, VR Technologies
Mike Fowler, Silent Diving
Christian Heylen, Pure Tech and Rebreather Ventures
Pete Mesley, Lust 4 Rust Diving Excursions
Dr. Nick Bird, Divers Alert Network
Keith Jeffries, U.S. Transportation Security Administration (TSA)

Q: What advice would you offer to dive operators and divers on dive safety and how divers can help plan for or mitigate field emergencies?

A: Diving involves taking on inert gas loads regardless of diving on open-circuit or a rebreather so the treatment of diving emergencies remains the same for all divers, and standard procedures should be used for dive planning and the treatment of symptoms relating to decompression sickness.

Q: How can we grow travel in the rebreather diving community and what can help make more dive shops and destinations rebreather friendly?

A: Have a supply of rebreather tanks, scrubber, check lists for various rebreathers, adequate staging areas, trained staff to guide and support rebreather divers and allowing for longer dive times and more dive boat space were deemed to be the basic essentials for being rebreather friendly.

Q: Are there standardizations that could occur from rebreather manufacturers that would make entry into the rebreather diving community more accessible and more affordable for dive shops and destinations?

A: Testing rebreathers on all absorbents could occur with published results, allowing divers to use various absorbents and know how long it would last. Rebreathers could be designed in the future for use with any size/type tank, allowing more flexibility in diver choices.

Q: What recommendations relating to TSA requirements would you have that allow divers to travel with rebreathers, scrubber, tanks, cells and batteries?

A: Communicating effectively and remaining calm are critical when dealing with TSA as not all security officers understand rebreathers or diving. Other recommendations include arriving at the airport in plenty of time, providing cellphone contact and content information externally on your luggage, and removing values from cylinders. Ask for the TSA customer service or stakeholder manager in advance of traveling with specialized equipment or in a group or when a TSA agent questions articles in your carry-on or luggage.

USS Aaron Ward, *Solomon Islands. Photo by Andrew Fock.*

THERMAL PHYSIOLOGY AND DIVER PROTECTION

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ABSTRACT

Thermal issues can substantially alter decompression stress. The impact will depend on the timing, direction and magnitude of the thermal stress. While divers may be cognitively and physically impaired by cold stress, reaching a true state of hypothermia would be highly unusual. Thermal protection can be provided by a variety of passive systems and an increasing number of active systems. Active systems must be used with particular care since they can markedly alter inert gas exchange and decompression risk. Increased decompression stress will be experienced by divers warm during descent and bottom phases and cool or cold during ascent and stop phases. Decreased decompression stress will be experienced by divers cool or cold during descent and bottom phases and warm during ascent and stop phases. Practically, it is important for divers to remember that while many dive computers measure water temperature, none assess the thermal stress actually experienced by the diver. While real-time monitoring might one day allow for dynamic decompression algorithm adjustment based on thermal status, the current diver must consciously manage thermal status and risk.

Keywords: cold stress, cold water, decompression, diving, hypothermia, immersion, insulation

INTRODUCTION

Diving is conducted across a broad range of conditions. Water temperatures can exceed 38°C (100°F) and be as low as -1.9°C (29°F). The duration of exposures can also be extreme, with examples of exploration dives lasting tens of hours (Kernagis et al., 2008). While thermal status is probably most obviously associated with individual comfort and then concentration and performance issues, it can also play a critical role in affecting decompression risk.

Thermal factors can have complex effects, either increasing or decreasing the net decompression stress, depending on the timing, direction and magnitude of the effect. The best demonstration of the fundamental relationships was provided by Gerth et al. (2007). This study was conducted at the U.S. Navy Experimental Diving Unit (NEDU) Ocean Simulation Facility. The study captured 73 male subjects (37±6 years of age; 27.6±3.1 kg·m^{-2} body mass index) completing 484 man-dives in eight series. Dives included full immersion and substantial exercise (at a rate of approximately seven times resting effort, or seven metabolic equivalents [MET]) in a wet chamber compressed to a pressure equivalent to a depth of 37 msw (120 fsw). The bottom phase was followed by a long decompression (87 minutes) that would accommodate increases in bottom time in the event that the rate of decompression sickness (DCS) stayed low during the study. The water temperature was clamped for two phases: descent/bottom and ascent/stop. Clamp temperatures were 36°C (97°F — "Warm") and 27°C (80°F — "Cold"). The study yielded 22 cases of DCS. The relative risk from high to low can be ranked as "Warm–Cold" (warm in the descent and bottom phases and cold in the ascent and stop phases), then "Cold–Cold," "Warm–Warm," and finally "Cold–Warm."

The results of the Gerth et al. (2007) study make sense intuitively since being warm during the descent and stop phase would augment inert gas uptake and being cold during the ascent and stop phase would impair inert gas elimination. Similarly, being cold during the descent and bottom phase would reduce inert gas uptake, and being warm during the ascent and stop phase would increase inert gas elimination. The surprising part was the magnitude of the effect. The "Warm–Cold" combination had a 30-minute bottom time and yielded 22 percent DCS, while the final "Cold–Warm" combination had a bottom time of 70 minutes and yielded only 0.1 percent DCS. While the decompression and stop phase of the dive was disproportionately long

Figure 1. A diver about to descend in slush-filled hole in Antarctica. Photo courtesy Neal Pollock.

in comparison with many operational dive profiles, the study clearly shows that thermal status can have dramatic effects. Far beyond comfort, this work reinforces the importance of understanding thermal issues associated with diving.

MAJOR AVENUES OF HEAT EXCHANGE

There are four primary avenues of heat exchange important in the diving environment: radiation, conduction, evaporation and convection. **Radiation** represents the electromagnetic energy radiating from any object to any cooler object separated by space (air or vacuum). **Conduction** represents the heat flow between objects in physical contact. Insulation represents the inverse of conduction. The standard unit of insulation is the "clo," with 1.0 clo approximating the insulative protection of a summer-weight British suit from the 1950s (1 clo = $0.18°C \cdot m^2 \cdot h \cdot kcal^{-1}$ = $0.155°C \cdot m^2 \cdot W^{-1}$ = $5.55\ kcal \cdot m^2 \cdot h^{-1}$). **Evaporation** represents the heat energy expended to convert liquid water to gaseous state. Evaporative heat loss results from humidifying inspired gases and the evaporation of sweat on the skin. **Convection** represents the heat flow through circulating currents in liquid or gas environment.

The concern in most diving environments is the minimization of heat loss. Even tropical waters can produce substantial cold stress over long exposures. Radiative heat loss is a relatively minor concern in diving. Vasoconstriction will decrease skin temperature, effectively reducing the radiative gradient. Radiative barriers have been added to the inside of some wetsuits and drysuits, but probably with little actual benefit given the minimal (or non-existent) physical separation.

Conduction is the primary avenue for heat loss in water. The heat capacity of water (density x specific heat) is >3500 times greater than air, yielding conductive loss rates 20-27 times greater than air. Protection against conductive losses is gained through improved insulation. The best insulator is a vacuum layer evenly distributed over the body surface. Next would be gas, then non-metals and, finally, the worst insulator would be highly conductive metals. The key to effective insulation is persistent loft, a challenge in drysuits since hydrostatic forces compromise loft by shifting air to the highest point of a suit during immersion.

Respiratory evaporative heat losses increase with depth as a function of increasing gas density. There is a high heat loss associated with breathing open-circuit gas that can fall far below ambient temperature upon expanding from the compressed source. Inspired gases must be heated during deep dives (Piantadosi and Thalmann, 1980; Burnet et al., 1990). Table 1 indicates minimum recommended inspired gas temperatures for open-circuit divers to avoid body cooling.

Table 1. Minimum recommended inspired gas temperatures for open-circuit deep diving.

Minimum T_{insp} (°C)	Minimum T_{insp} (°F)	Depth (msw)	Depth (fsw)
-3.1	26.4	107	350
1.2	34.2	122	400
7.5	45.5	152	500
11.7	53.1	183	600

Closed-circuit rebreathers reduce respiratory evaporative heat loss by retaining high humidity in the closed loop. The exothermic carbon-dioxide scrubber reaction warms the circulating gas sufficiently to provide additional thermal benefit.

Evaporative heat loss from the skin is not a concern in high relative humidity environments. A fully saturated environment exists during unprotected immersion or in a wetsuit. A fully saturated environment develops very quickly in a sealed drysuit.

Convective heat loss can vary substantially, depending on the stability of the near-skin microclimate. Drysuits provide a stable environment, wetsuits provide a reasonably stable environment if the design and fit effectively minimize water circulation. Convective losses can be substantial in a poorly fitting wetsuit.

UNPROTECTED COLD WATER IMMERSION

Even the modest protection of a poorly fitting wetsuit or drysuit likely provides sufficient thermal protection for hypothermia to be extremely unlikely to develop in most divers. It is, however, possible that unprotected immersions or extreme expeditionary dives can produce significant stress. For that reason, extreme impacts should be understood.

The response to unprotected cold water immersion can be described as four phases. The first is characterized by the initial immersion response or 'cold shock' that develops in the first two minutes. In this phase heart rate, respiratory rate and blood pressure rapidly increase and cerebral blood flow velocity decreases as hyperventilation reduces the carbon dioxide level in the blood (Mantoni et al., 2008). The impact of cold shock increases as water temperature falls below 15°C (59°F).

The second phase is characterized as short term immersion or 'swimming failure.' A rapid chilling of superficial skeletal muscles creates a crippling weakening much faster than is likely expected. This is an effect of the conductive heat sink provided by water. It is this phase that is most likely to kill unprotected swimmers that do not have sufficient buoyancy for their airway to remain protected.

The third phase is described as long-term immersion, when hypothermia might develop. The evolution of hypothermia will vary dramatically with thermal protection, total mass, surface-to-volume ratio, the amount of subcutaneous fat to serve as passive insulation, the amount of skeletal muscle able to generate heat through shivering, and water temperature. Average rates of core temperature decline in human immersion studies range from 0°C·h^{-1} at 25°C (77°F), -0.75°C·h^{-1} at 18°C (64°F), -2.6°C·h^{-1} at 10°C (50°F) (Tipton et al, 1999), through -3.9°C·h^{-1} at 4.6°C (40°F) (Hayward et al., 1975) and -6°C·h^{-1} at 0°C (32°F) (Hayward and Eckerson, 1984). As mentioned previously, a victim will survive to this stage only if an effective airway is maintained.

Core temperature is normally maintained at 37±1°C (98.6±2°F). Mild hypothermia is defined as a core temperature of 35-32°C (95-90°F); moderate hypothermia 32-28°C (90-82°F), and severe hypothermia <28°C (82°F). Mild hypothermia poses little risk to an otherwise healthy individual, moderate hypothermia can be associated with cardiac dysrhythmias, and severe hypothermia can lead to serious dysrhythmias or cardiac failure.

The fourth phase describes the critical period when a victim is rescued from significant cold immersion. A combination of handling stress, loss of hydrostatic pressure secondary to removal from the water, and increased circulatory demands to accommodate postural changes can all act to produce "circum-rescue collapse" (Golden et al., 1991). The impaired cardiac function associated with high-moderate or severe hypothermia is more likely to be associated with collapse. It is critical that patient vitals are closely monitored through the removal and postremoval period since physiological collapse is possible.

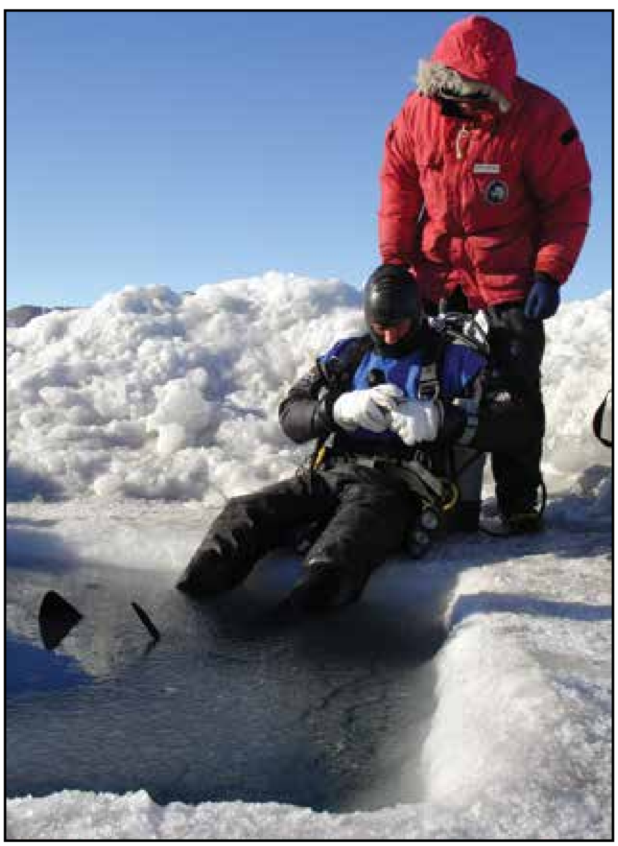

Figure 2. Diver being tended prior to diving through an open hole in Antarctica. Photo courtesy Neal Pollock.

A postexposure decrease in core temperature ("afterdrop") often follows the end of cold exposure. An extreme example was described in a diver completing a 43-minute dive in -1.9°C (28.6°F) seawater in a failed drysuit in the Antarctic. A stable predive rectal temperature of 36.1°C (97.0°F) declined to a minimum of 34.8°C (94.6°F) following the dive (Pollock, 2007). While afterdrop is not always a problem, it is important to be aware that a victim close to serious core temperature depression could experience a continued drop after removal from the cold stress. Contributing mechanisms for afterdrop include attenuated shivering thermogenesis as the skin is warmed and cutaneous cold receptors become less active; by conductive heat loss along tissue thermal gradients; and by convective cooling via changes in peripheral blood flow (Webb, 1986; Giesbrecht and Bristow, 1998).

NON-HYPOTHERMIA COLD INJURY

Divers tend to focus on DCS even though other injuries can occur. A recent case report described numbness and paresthesia and then a waxing and waning burning sensation in the left hand and forearm after a 90-minute dive to a maximum depth of 27 msw (90 fsw) in 6°C (43°F) water. The initial suspicion of DCS was replaced by the diagnosis of a non-freezing cold injured instigated by a tight computer strap on the afflicted wrist (Laden et al., 2007).

THERMAL PROTECTION FOR COLD-WATER DIVING

Passive insulation can be provided by wetsuits or drysuits. Active insulation can be provided by electrically heating garments or hot-water suits. Standard foam neoprene is compressed by pressure, reducing the insulation and altering the fit. Standard neoprene can lose on the order of three-quarters of its insulation at 405 kPa (4 atm) pressure.

The thermal protection of drysuit systems is generally provided by a three-layer strategy. The **base layer** is hydrophobic to wick water away from the skin. In air environments the physical distance between the moisture and the skin limits evaporation and, by extension, evaporative heat loss. This is not the case in the high relative humidity environment of the closed drysuit. Instead, the water is wicked away from the skin to reduce conductive heat loss to the liquid. The **mid-layer** of the drysuit provides insulation, further reducing conductive heat loss. The outermost **shell layer** provides a barrier to reduce convective heat loss.

Drysuits may be made from standard neoprene, thin shell suits made from a variety of materials, or crushed neoprene formed under greater pressure than standard neoprene. As with wetsuits, the insulation of standard neoprene drysuits is compromised by pressure increase. The insulation provided by shell suits is typically stable but modest thermal protection, often ~0.2+ clo. Crushed neoprene generally provides greater and more stable insulation, possibly ~0.6 clo throughout the typical diving range.

The undergarments and trapped gas typically provide the majority of the insulation in a drysuit system. Some garments with extremely high loft have been marketed. Problematically, if these materials are easily compressed, they will perform better on the surface than when compressed by hydrostatic pressure during immersion. Thinsulate™ has been the closest to a standard in diving undergarment insulation for the past 20 years, but it has only partially satisfied thermal protection needs. Recent efforts have been directed at integrating rigid forms into garments to limit loft loss and stabilize insulation layers. This can be seen in undergarments such as the Fourth Element Halo 3D or integrated into the inside of the suit like the Waterproof® D1 Hybrid. Ongoing efforts are directed at impregnating aerogel into undergarments. Aerogel is a low-density, highly porous silica matrix with extremely low thermal conductivity. It was developed in the 1930s for the aviation industry. The goal is to encapsulate the aerogel into a bat matrix of other materials to overcome the relative fragility and inflexibility of aerogel. Thermal manikin studies of premarket test suits identified a 149 percent increase in insulation using an aerogel-impregnated undergarment in comparison with a commercial undergarment (air was used as the inflation gas for both) (Nuckols et al., 2008). While the final benefits may be reduced, the potential exists for substantial improvement over similar Thinsulate™ garments.

Argon has been promoted as a drysuit inflation gas to improve thermal protection. Theoretically, the 30-percent lower thermal conductivity could produce a 48-percent increase in suit insulation in comparison to air (1.92 vs. 1.30 clo, respectively) (Lippitt and Nuckols, 1983). However, a double-blind field study found no benefit of argon vs. air. The argon fill did not improve skin temperature, core temperature or perceived thermal comfort (Risberg and Hope, 2001). It is likely that hydrostatic pressure forcing the gas bubble to the highest point of the suit obviated the possibility of the gas forming a stable boundary layer over the skin and contributed to the lack of impact. Another practical issue in using argon is that substantial volumes are required to fully flush air out of a suit. Nuckols et al. (2008) conducted a manikin study in dry air and found a 16-20 percent improvement in insulation with argon vs. air, but it required ≥6 fill/clear cycles to adequately purge air from the suit.

Combining argon with an undergarment that preserves gas channels may offer some improvement, but a significant benefit of argon use may be limited to long, expeditionary dives when small improvements in thermal protection can be meaningful. For most dives, a much greater thermal benefit is likely to be gained from improved insulating designs and materials.

In-suit electric heating is now available for both wetsuits and drysuits. Battery-powered systems can provide multiple power settings and multiple zones. While these systems may substantially improve personal comfort, they also have the potential to increase decompression stress by promoting the uptake of inert gas when used during the descent and bottom phase of a dive. Reduced efficacy, or worse, a complete heating system failure later in the dive would produce the "Warm–Cold" situation shown to dramatically increase decompression stress in the Gerth et al. (2007) study. Disciplined use of active heating

Figure 3. Diver preparing to dive through a hole in the ice at Gneiss Point, Antarctica. Photo courtesy Neal Pollock.

systems could reduce the hazard, for example, by only turning it on at the end of the bottom phase. There are legitimate concerns with this approach as to whether the system will activate appropriately at that time or if it will be sufficient to provide comfort and improve decompression outcome. A compromise for systems that provide multiple heating levels would be to keep it on the lowest setting during the descent and bottom phase and then adjust it to a higher setting for the ascent and stop phase. It remains to be seen if concerns over decompression risk will outweigh personal comfort and keep these devices compatible with decompression safety.

While little research data are available on the decompression hazard associated with electrically heated garments, there is a reasonable body of literature addressing similar concerns with hot-water suits. Primarily used in commercial operations, hot water is pumped into a wetsuit that distributes the water around the diver's body before it escapes to the environment. As an added benefit in deep dives, the heated water may pass through a heat exchanger to warm the inspired gas. Hot-water suits have been clearly associated with an increased risk of DCS in comparison with passive insulation (Shields and Lee, 1986; Leffler and White, 1997; Leffler, 2001). A secondary concern is that actively warming the skin will effectively incapacitate the cold receptors that are primarily located in the skin. This has been suggested to inhibit physiological response to respiratory cooling (Hayward and Keatinge, 1979). Hypothermia unawareness has been described if respiratory heat loss causes a rate of core temperature decline less than 0.7°C·h^{-1} (1.3°C·h^{-1}) (Piantadosi et al., 1981). A later study of commercial hot-water suit diving found that core temperature was adequately protected by the current practices (Mekjavic et al., 2001). This study did not assess decompression stress.

MONITORING THERMAL STATUS AND DECOMPRESSION STRESS

Thermal stress is determined by the thermal protection worn, diver habitus and physical activity. It is not determined by water temperature, which is the only thermal measure captured by existing dive computers. Current decompression algorithms do not assess the impact of thermal stress, which is an important shortcoming considering that thermal status can substantially influence decompression safety. While real-time monitoring might one day allow for dynamic decompression algorithm adjustment based on thermal status, the best protection for current divers is a thorough appreciation of the hazards and thoughtful decision-making that favors safety, even if at the expense of comfort. Efforts to avoid the "Warm–Cold" dive profile should be a minimum target; maintaining a subtle "Cool–Warm" pattern may be optimal, as long as the warming is not achieved by physical effort that may also promote bubble formation. Increasing decompression safety buffers for thermal conditions that are less than optimal is good practice.

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DECOMPRESSION METHODS

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ABSTRACT

Decompression algorithms prescribe ascent rates (typically by scheduling decompression stops) to limit the risk of decompression sickness. The measured depth/time/breathing-gas history of a dive is used to calculate an index of decompression stress based on theoretical tissue gas uptake and washout and bubble formation. Different decompression strategies, including deep stops and switching between breathing gases, have been thought to increase the efficiency of decompression schedules.

Keywords: air, bubbles, decompression model, decompression sickness, deep stops, heliox, model

INTRODUCTION

Decompression sickness (DCS) is an injury thought to be caused by bubbles that form in the body from excess dissolved gas upon reduction in ambient pressure (decompression). Haldane and colleagues (1908) developed the first practical decompression model and produced the first decompression schedules for diving that minimised the risk of DCS by controlling the depth and duration of the dive and the decompression rate (Boycott et al., 1908). This and subsequent decompression models link the risk of DCS to an index of decompression stress calculated from the depth/time /breathing-gas history of a dive. Decompression models developed and tested based on experimental dives can then be used to predict the outcome of future, similar dives and therefore be used to produce decompression schedules. This paper provides a brief overview of the two principal methods of calculating decompression stress from the depth/time/breathing-gas history. The paper then looks at two areas relevant to technical diving, the differences in decompression schedules between traditional gas content models and bubble models and the differences in decompression schedules resulting from switching between helium-based and nitrogen-based breathing gases.

DECOMPRESSION STRESS

DCS probably results from bubbles formed in body tissues so a natural choice of decompression stress is the number and size of bubbles. The actual bubbles that cause DCS have not been measured, not least because their size, number, and location have not been identified. Some intravascular bubbles can be detected by ultrasonic methods (Doppler shift or echocardiography), and there is a correlation between these venous gas emboli (VGE) and DCS (Nishi, 1993), but these VGE do not cause all forms of DCS. Therefore, in decompression models, decompression stress is not a measured quantity but rather a theoretical index calculated from the characteristics of the dive thought to influence probability of decompression sickness, typically the depth/time/breathing-gas history. Decompression stress is typically a calculated index of bubble number or volume (bubble models) or of the excess gas in tissues that drives bubble growth (gas content models).

INERT GAS UPTAKE AND WASHOUT

The uptake and washout of gas into body tissues based on depth/time/breathing-gas history is common to both model classes. Because breathing gas must be delivered at ambient pressure, with the increase in ambient pressure encountered in underwater diving, gas from the breathing mixture is absorbed into the body tissues (blood, muscle, spinal cord, etc.) during a dive. Over time, the concentration of inert gas (usually nitrogen or helium) dissolved in the tissues approaches equilibrium with the inspired gas partial pressure. Excess inert gas is eliminated from tissues both during and after ascent. The dominant route of inert gas into and out of the blood is via the lungs. Nitrogen and helium equilibrate rapidly between the lungs and arterial blood; therefore, over a time course relevant to calculating decompression schedules, only exchange between the arterial blood and the tissues needs to be considered. The main factor that determines tissue uptake and washout of gas is the rate at which gas is carried in the blood that perfuses the tissue, although these kinetics are influenced by diffusion processes (Doolette and Mitchell, 2011).

The most common structural model of gas uptake and washout is the single exponential tissue compartment where the rate limiting process is usually considered blood perfusion. Underlying this model is the assumption that, owing to rapid diffusion, equilibration of inert gas concentration gradients across the tissue region represented by the compartment is much faster than transport in and out of the compartment. In this model, arterial-tissue inert gas tension difference declines mono-exponentially according to a half-time notionally determined by the blood flow to the tissue compartment and relative solubility of the gas in the blood and the tissue compartment. Figure 1 shows mono-exponential uptake and washout of an inert gas from one such compartment. Several (typically 3 to 16) parallel perfusion-limited compartments with different half-times are used to accommodate different rates of gas uptake and washout across the relevant body tissues.

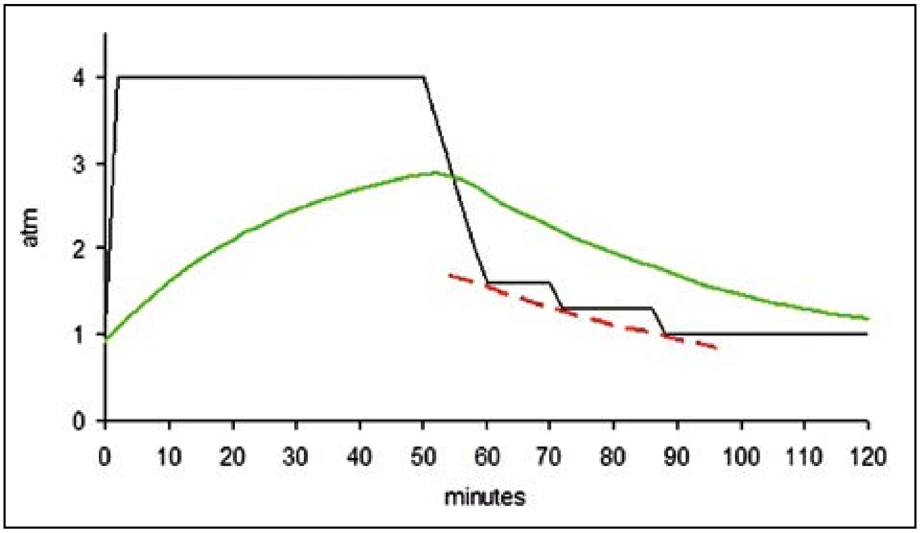

Figure 1. Exponential approach of tissue gas pressure (P_{tis}, green line) to arterial gas pressure (not shown) with changing ambient pressure (P_{amb}, black line) during a 100 fsw (30 msw) dive. The Haldane-style safe ascent depth is shown as a dashed line (see the gas content model section for explanation).

BUBBLE FORMATION

If the sum of inert gas and metabolic gas (oxygen, carbon dioxide, water vapour) tissue compartment tensions (concentration/solubility, units of pressure; P_{tis}) exceeds ambient pressure (P_{amb}) during or after decompression, gases can leave solution, forming bubbles in tissues and blood. In Figure 1, the supersaturation ($P_{ss}=P_{tis}-P_{amb}>0$) for this particular compartment can be visualized as the vertical distance between the P_{tis} and P_{amb} lines, where $P_{tis}>P_{amb}$.; this is also illustrated by the vertical bars in Figure 2.

The pressure inside a bubble (P_{bub}) is the sum of the external pressures applied to the bubble including ambient pressure, pressure due to surface tension, and any mechanical effect from the tissue. Ignoring the latter factor for simplicity:

$$P_{bub}=P_{amb}+2\gamma/R_{bub} \qquad (1)$$

where γ is surface tension and R_{bub} is bubble radius. P_{bub} exceeds ambient pressure for small bubbles but approaches ambient pressure for mechanically stable, large (e.g., ultrasonically detectable) bubbles. Therefore, for a bubble to form:

$$P_{tis}-P_{amb}=P_{ss}>2\gamma/R_{bub} \qquad (2)$$

The extent of supersaturation not only determines the probability (or the rate) of bubble formation but also bubble growth. If the partial pressure of gases inside a bubble exceeds the tissue gas tensions, the bubble will shrink; conversely, bubbles of sufficient size can grow, acquiring gas by diffusion from the supersaturated tissue.

GAS CONTENT DECOMPRESSION MODELS

Since supersaturation determines the probability or rate of bubble formation and represents the driving force for bubble growth, it has been used as an index of decompression stress. Gas content models schedule ascent rate and decompression stops according to ascent rules that limit supersaturation without directly calculating any bubble index. This principle was introduced by Haldanae and colleagues (Boycott et al., 1908). A widely used format for ascent rules is (Workman, 1969):

$$P_{tis\_inert}<z\cdot P_{amb}+w \qquad (3)$$

where P_{tis_inert} is the tissue inert gas tension and z and w should be experimentally derived constants. A useful form of Equation 3 is:

$$SAD=P_{amb\_tol}=(P_{tis\_inert}-w)/z \qquad (4)$$

Where the safe ascent depth (SAD) is the minimum tolerated ambient pressure (P_{amb_tol}). The SAD is illustrated in Figure 1. This format is used in the ZH-L16 gas content model (Bühlmann, 1988), upon which many diver-carried decompression computers and user-controllable decompression software is based. To calculate decompression according to a content model, P_{tis_inert} and SAD is calculated for each compartment (16 in the full ZH-L16 model) according to the preceding depth/time/breathing-gas history. Decompression stops may be required so that the P_{amb} is never lower than the SAD as illustrated in Figure 1.

BUBBLE DECOMPRESSION MODELS

There are two general classes of bubble decompression models, although they have overlapping aspects. One class focuses on the dynamics of bubble growth and dissolution due to gas diffusion between bubbles in the surrounding tissue (Gernhardt, 1991; Gerth and Vann, 1997). The second class of models is much simpler, focusing on the number of bubbles that can form during decompression (Yount and Hoffman, 1986). These bubble counter models will be outlined here because they are widely available to technical divers (Wienke, 1990; Yount et al., 2000).

Equation 2 describes the inverse relationship between bubble size and the supersaturation required to form that bubble. Supersaturation of more than 100 atm is required to form bubbles in purified water. However, in humans, VGE can be detected with supersaturation less than 1.36 atm (Eckenhoff et al., 1990). It seems likely, therefore, that such bubbles result from accumulation of gas into or around pre-existing gas nuclei (theoretical "proto-bubbles"). One theoretical form of gas nucleus is coated with surface active agents that counteract surface tension and render the gas nucleus relatively stable.

In the varying permeability model (VPM) (Yount and Hoffman, 1986), this surface active coating makes available a population of stable gas nuclei, some of which are sufficiently large that they can be activated into growing bubbles by supersaturation of the extent encountered in normal diving. For any particular sized gas nucleus from the population before a dive, the supersaturation subsequently required for growth is described by an equation similar to Equation 2 except that the right-hand side has additional terms that account for the difference in opposing forces of surface tension and the surface active agents and for compression of the gas nuclei during descent. Ignoring these additional terms for simplicity, Equation 2 can be rearranged to give:

$$R_{min}=2\gamma/P_{ss} \qquad (5)$$

where R_{min} is the radius of smallest gas nuclei that will be activated by any particular level of supersaturation.

By assuming a theoretical distribution of radii for the population of gas nuclei and substituting Equation 5 into the equation describing that distribution, the number of gas nuclei activated into growing bubbles can be calculated for the maximum supersaturation encountered during decompression. For completeness, but with no further explanation, the model name refers to the hypothesis that the surface active coating becomes impermeable to gas diffusion, and therefore gas nuclei behaviour changes, with compression beyond approximately 9 atm.

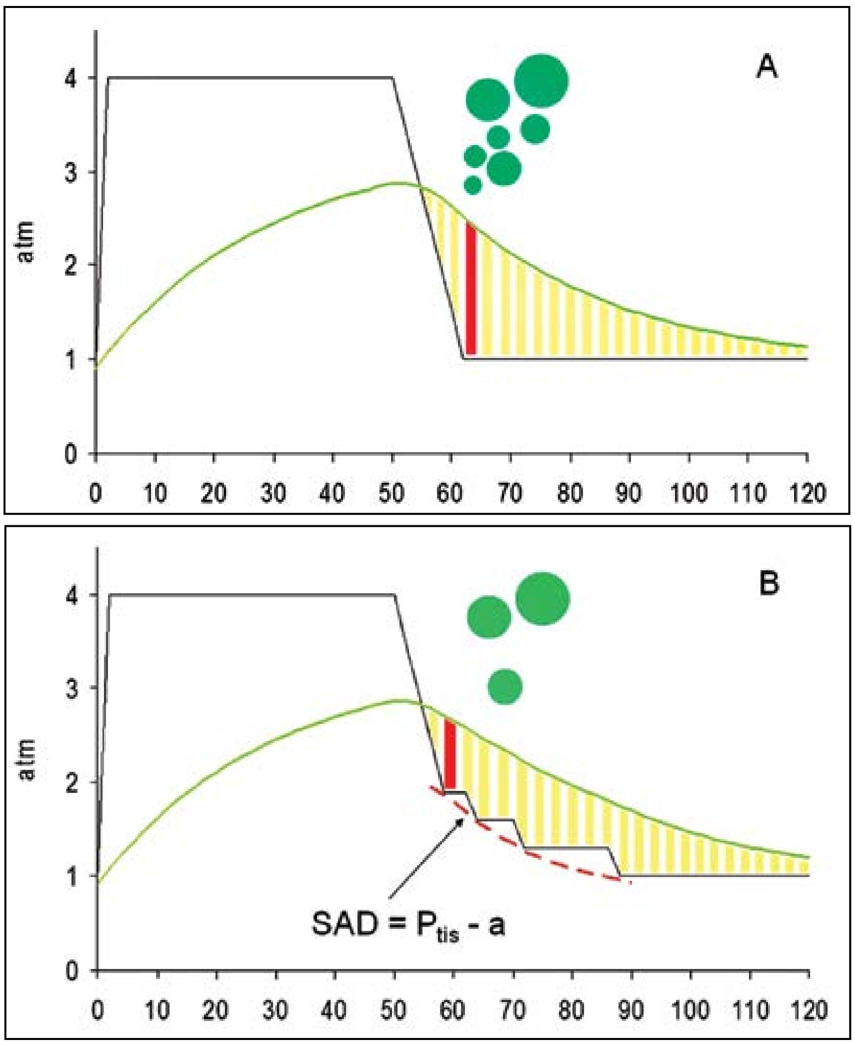

Figure 2. Bubble-counting models such as VPM limit the theoretical number of bubbles that form on ascent to the first decompression stop. In Panel A, ascent to the surface results in a large supersaturation, indicated by the vertical bars, which in turn results in formation of numerous bubbles. In Panel B, the smaller supersaturation causes only the largest gas nuclei to grow, and therefore fewer bubbles are formed. A target "safe" number of bubbles defines the maximum allowed supersaturation and consequently a safe ascent depth (SAD) for the entire decompression.

In the simplest form of VPM, decompression can be controlled by a maximum allowed number of bubbles and therefore a maximum allowed supersaturation. This is illustrated in Figure 2. Alternatively, decompression can be controlled by a maximum allowed index of bubble gas volume calculated using the simple approximation of multiplying the excess number of bubbles (total number minus an always safe number) by the integral of supersaturation and time (this is the area indicated by the vertical bars in Figure 2) out to some long cut-off time after decompression.

DEEP STOPS

A characteristic of bubble models is they typically prescribe deeper decompression stops than gas content models. The potential benefit of these bubble-model-prescribed "deep stops" has been hypothesized since the 1960s (Hills, 1966). Deep stops came to the attention of early technical divers in the form of "Pyle stops" used to slow the ascent to gas-content-model-prescribed first stop (Pyle, 1997). Deep-stop decompression schedules have long been a part of technical diving practice, and many thousands of decompressions have been conducted safely. It is deeply entrenched in technical-diving folklore, based on anecdotal evidence, that deep-stop decompression schedules are more efficient than shallow-stops schedules — in other words, compared to shallow stops prescribed by a traditional gas content model, a deep stops schedule of the same or even shorter duration has a lower risk of DCS. Recently, however, evidence has been accumulating from laboratory man-trials that shows deep stops are not more efficient than shallow stops for air or trimix dives (Blatteau et al., 2009; Doolette et al., 2011).

NEDU Deep Stops Trial

The largest of these trials was conducted at the U.S. Navy Experimental Diving Unit (NEDU). Divers breathing surface-supplied air via MK-20 UBA, immersed in the NEDU Ocean Simulation Facility were compressed to 170 fsw (52 msw) for a 30-minute bottom time during which they performed 130-watt cycle ergometer work. They were then decompressed at 30 fsw·min^{-1} (9 msw·min^{-1}) with stops prescribed by one of two schedules shown in Figure 4. Divers worked while on the bottom and were at rest and cold during decompressions — conditions that require long decompression schedules. The shallow stops schedule, with a first stop at 40 fsw (12 msw) and 174-minute total stop time, was prescribed by the gas content VVal18 Thalmann Algorithm. The deep stops schedule, with a first stop at 70 fsw (21 msw), was the optimum distribution of 174-minute total stop time according to the probabilistic BVM(3) bubble model (Gerth and Vann, 1997). A higher incidence of DCS was observed on the deep-stops schedule (Figure 3). Divers were also monitored for VGE with transthoracic cardiac two-dimensional echo imaging, at 30 minutes and two hours after surfacing, both at rest and after limb flexion. The maximum VGE grade observed was significantly higher after the deep-stops schedule (median=3) than after the shallow-stops schedule (median=2, Wilcoxon rank sum test, W=12967, p<0.0001).

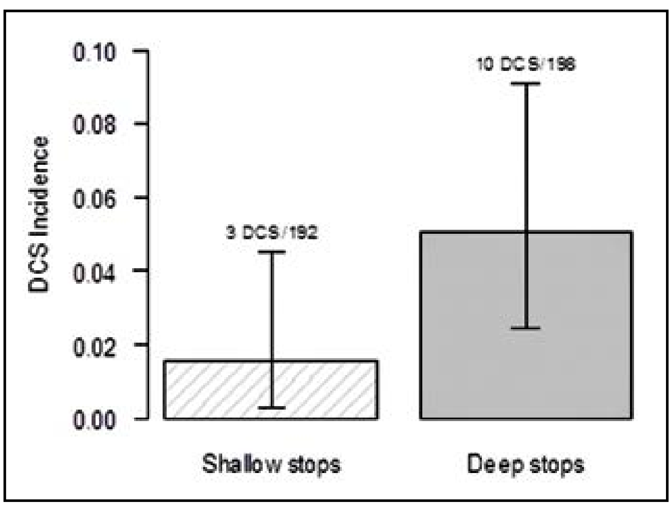

Figure 3. Observed DCS incidence and binomial 95 percent CI in the NEDU deep-stops trial. Actual number of DCS and number of man-dives are indicated above the bars (#DCS/#dives). The deep-stops schedule had a significantly higher incidence of DCS than the shallow-stops schedule (p=0.0489, one-sided Fisher's Exact test). From Doolette et al. (2011).

The BVM(3) bubble model predicts growth and dissolution of bubbles in three theoretical tissue compartments and indicated substantial bubble growth on the shallow stops schedule in the fast compartments (1- and 21-minute half-times) that required "repair" with deep stops (Gerth et al., 2009a). However, interpreting the NEDU result does not require a full bubble model but simply a clear understanding of the relationship between tissue gas kinetics and bubble formation. There are four important facts to keep in mind: 1) bubbles form and grow only if the tissue is gas supersaturated, and the greater the supersaturation the more bubbles will form and the faster they will grow; 2) supersaturated tissue has higher inert gas tension than arterial blood has, so inert gas also diffuses from supersaturated tissue into the capillary blood and is washed out — tissues that contain bubbles are losing, not taking up, inert gas; 3) once inert gas washout has reduced inert gas partial pressure in tissue below that inside the bubble, the bubble shrinks; and 4) inert gas uptake and washout occurs at different

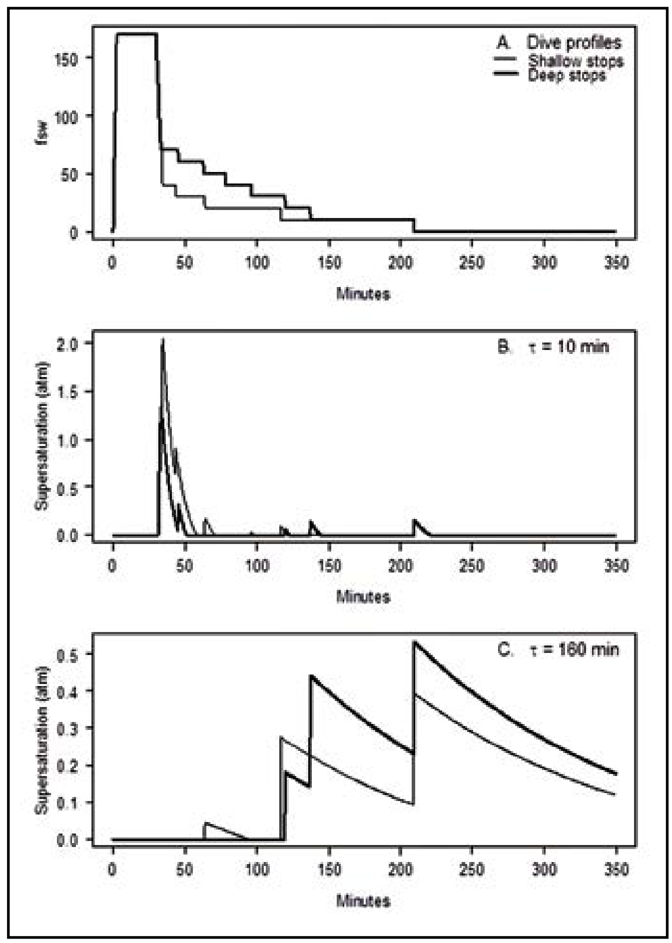

Figure 4. Supersaturation ($\Sigma P_{tisj} - P_{amb} > 0$) in fast and slow compartments for the tested shallow-stops and deep-stops schedules. A. Overlay of the two 170 fsw (52 msw) / 30-minute air decompression dive profiles tested. B. Supersaturation in a modeled compartment with fast (τ = 10 minutes) mono-exponential inert gas exchange. C. Supersaturation in a modeled slow (τ = 160 minute) compartment. From Doolette et al. (2011).

rates in different body tissues, and these different rates can be represented by compartments with different half-times.

Figure 4B shows gas supersaturation in a fast inert gas exchange compartment for the tested shallow- and deep-stops dive profiles illustrated in Figure 4A. This fast compartment (time constant, τ = 10 minutes, equivalent to half-time = 7 minutes) is representative of all compartments that have comparatively fast gas exchange and in which an ascent to the shallow first decompression stop results in gas supersaturations greater than those produced by an ascent to a deeper first stop. The fast compartment in Figure 4B displays markedly lower and less sustained gas supersaturation (and therefore less driving force for bubble formation) during the comparable period of the shallow stops schedule. This is consistent with the observation that a brief deep stop results in less Doppler detectable VGE during decompression (Neuman et al., 1976). The NEDU results indicate that this reduction of gas supersaturations in fast compartments does not manifest in reduced DCS incidence — the large ascent to the first stop in traditional schedules is not a flaw that warrants repair by deeper initial stops.

Figure 4C shows supersaturations in a slow compartment (τ = 160 minutes, half-time = 111 minutes) representative of all compartments having comparatively slow gas exchange and which are not gas supersaturated upon ascent to the deep first decompression stop. Inert gas will either washout slowly or continue to be taken up into these slow compartments at deep stops. Therefore, deep stops result in greater and more persistent gas supersaturation in slow compartments on subsequent ascent than during the comparable period in the shallow-stops schedule. Gas supersaturations in slower gas exchange compartments late in the decompression are in accord with the present results from the tested dive profiles. The observed higher VGE scores and DCS incidence following the deep stops schedule than following the shallow stops schedule must be a manifestation of bubble formation in slower compartments.

Although the tested shallow- and deep-stops schedules are the optimal distributions of stop time under the VVal-18 Thalmann Algorithm and BVM(3) models, respectively, this does not mean that either schedule is the true optimal distribution of 174 minutes total stop time. Of interest is how alternative deep-stops schedules might have performed against the traditionally shaped shallow-stops schedule. Figure 5 shows the two schedules tested in the NEDU trial and a deep-stops schedule prescribed by VPM-based decompression software available to technical divers, that has deeper and short initial decompression stops than the tested deep-stops schedule. Analysis of half a million alternative schedules show the same patterns as illustrated for the tested schedules in Figure 4 — deeper stops reduced supersaturation in fast compartments at the expense of increased supersaturation in slow compartments compared to shallow-stops schedules (Doolette et al., 2011). Several air and trimix schedules with brief deep stops, more like those conducted by technical divers, have been compared to traditional shallow-stops schedules using VGE as an endpoint in a limited number of man-dives. Despite longer decompression times, the deep-stops schedules resulted in the same or more VGE than the shallow-stops schedules, and some deep-stops dives resulted in symptoms of DCS (Blatteau et al., 2005; Blatteau et al., 2009).

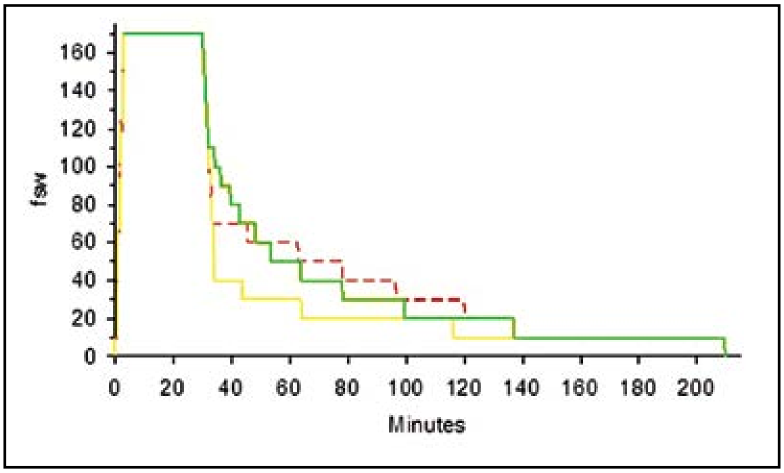

Figure 5. Comparison of the shallow- (yellow line) and deep-stops (red dashed line) schedules tested in the NEDU trial with a schedule produced by VPM decompression model (heavy green line), with parameters adjusted to give the same total stop time as the NEDU schedules.

Although deep stops do not allow a decrease in decompression time compared to traditional gas content decompression schedules, some forms of deep stops are useful. The laboratory studies used slow ascent to the first stop (30 fsw·min^{-1} [9 msw·min^{-1}] in the NEDU study), and brief stops are an effective method to produce a slow ascent rate in the water. Of relevance to the present proceedings is the impact of the technical-diving practice of switching to a high fraction oxygen decompression gas at a deep stop or diving with a constant PO_2 closed-circuit rebreather. Such gas mixtures accelerate decompression by faster washout of inert gas from all compartments but will also result in less uptake of inert gas into slow compartments during deep stops. For instance, if the NEDU schedules in Figure 4 incorporated a switch to 50 percent O_2 / 50 percent N_2 at 70 fsw (21 msw), the supersaturations in slow compartments in Panel C would be greatly reduced for both schedules. The risk of DCS would be reduced for both schedules, probably so that it would not be possible to distinguish a difference in DCS incidence between the schedules. This is a result of the change in gas mixture, not the stop depth distribution (Gerth et al., 2009a; Gerth et al., 2009b). In addition, conducting adequate decompression prior to making breathing-gas switches may reduce the risk of some rare forms of DCS associated with breathing-gas switches (Doolette and Mitchell, 2003).

DIVING WITH MULTIPLE INERT GASES

Owing to differing physicochemical properties in some body tissues, helium is taken up and washed out faster than nitrogen. This difference can be seen in the whole body washout of helium or nitrogen and appears to be important in tissues with slow gas exchange, probably fat (Behnke and Willmon, 1940; Duffner and Snider, 1958; Doolette and Mitchell, 2011). This slower washout of nitrogen in slowly exchanging tissues is manifest in a slower required rate of decompression from nitrox (N_2-O_2) saturation dives (where the body has completely equilibrated with the elevated nitrogen partial pressure) than from heliox saturation dives (Eckenhoff and Vann, 1985).

A similar phenomenon is thought to be active in bounce dives, and in many decompression models helium is assumed to have faster exchange than nitrogen in all compartments. For instance, in the Buhlmann ZH-L16 gas content decompression model (Bühlmann, 1988), each of the 16 compartments has a half-time for helium that is 2.65-fold shorter than the corresponding nitrogen half-time. These, or similar, compartment half-times are used in most decompression models available to technical divers. As a result of these compartment half-times, such decompression models will prescribe less decompression obligation for a bounce dive conducted breathing nitrox than for a dive conducted breathing trimix or heliox because of a slower uptake of nitrogen than helium. Similarly, such decompression models will prescribe shorter decompressions if switching to nitrox breathing during decompression from a heliox or trimix dive. The reason for this latter effect is illustrated in Figure 6, which shows that faster helium washout than nitrogen uptake in a compartment will result in a period of undersaturation (making the SAD shallower) following a heliox-to-nitrox gas switch.

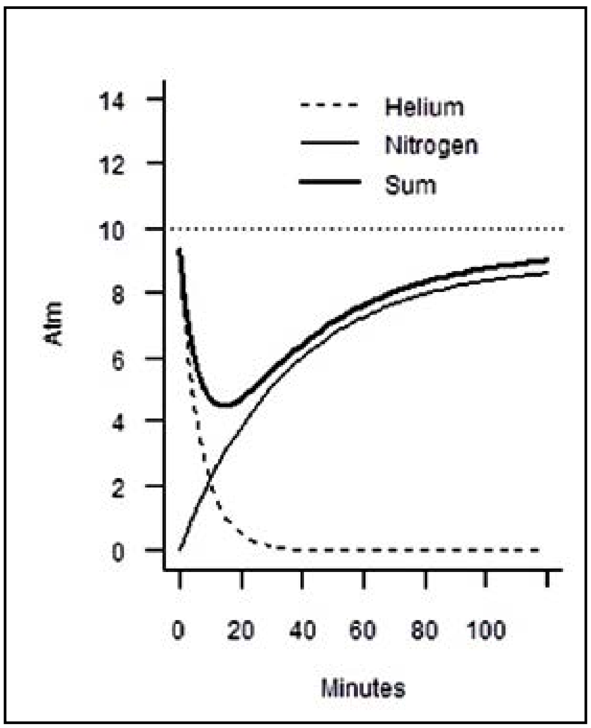

Figure 6. Isobaric exchange of helium and nitrogen in a compartment with faster half-time for helium than nitrogen. Simulation of a compartment at equilibrium with O_2 90% N_2 - 10% O_2 inspired gas at 10 atm abs ambient pressure and a switch to 90% He - 10% inspired gas at time zero. Dashed and thin lines indicate partial pressures of helium and nitrogen. The thick line indicates the sum of both inert gases and metabolic gases. The compartment is transiently undersaturated while the sum of gases is below the equilibrium value. Adapted from Doolette and Mitchell (2011).

HELIOX TO NITROX GAS SWITCH DOES NOT ACCELERATE DECOMPRESSION

It is not clear that the apparent differences in bounce diving decompression resulting from different inert gases are real. Indeed, direct measurement of helium and nitrogen exchange rates in faster exchanging tissues relevant to bounce diving indicates very similar rates of exchange for nitrogen and helium (Doolette et al., 2004; Doolette et al., 2005). The often-cited work supporting accelerated decompression by switching from heliox to nitrox (Keller and Bühlmann, 1965) in fact shows nothing of the sort. This work presents several dives with changes in inert gas composition and increases in oxygen fraction up to 100 percent during decompression and compares decompression time to U.S. Navy 1957 standard air schedules that were not actually dived. On the other hand, a U.S. Navy man-trial indicates that a heliox to nitrox switch does not accelerate decompression (Survanshi et al., 1998). In that study, 32 man-dives at 300 fsw (91 msw) for 25 minutes breathing 1.3 atm PO_2-in-helium for the entire bottom time and decompression resulted in only one case of DCS, whereas 16 man-dives with identical depth-time profile and inspired PO_2 but a switch to nitrox at the first decompression stop (110 fsw [34 msw]) resulted in three cases of DCS.

SUMMARY

The present paper provides an overview of how the measured depth/time/breathing-gas history of a dive is used to calculated decompression stress based on gas uptake and washout and bubble formation. Bubble decompression models prescribe deeper initial decompression stops than the traditional gas-content decompression models. Recent laboratory evidence suggests that traditional shallow-stops schedules are more efficient than deep-stops schedules. Many decompression models use a faster half-time for helium than for nitrogen in all tissue exchange compartments. A consequence of this compartment structure is a reduction in prescribed decompression time by switching to a nitrox breathing-gas mixture during decompression from a heliox bounce dive compared to remaining on heliox throughout the dive. However, laboratory data does not support this acceleration of decompression. It is not the intention of this review to discourage the practice of either deep stops or heliox-to-nitrox breathing-gas switches during decompression — there are theoretical reasons why both can be useful that are not covered in this review — but to show that that the output of any particular decompression algorithm is not always in accord with experimental evidence.

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Kevin Gurr test dives the Hollis Explorer hybrid rebreather, and Rosemary E. Lunn dives the AP Evolution rebreather on the USS Kittiwake *during Divetech's Inner Space. Photo by Jay Easterbook/Divetech.*

PHYSIOLOGY OF REBREATHER DIVING

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ABSTRACT

Carbon dioxide (CO_2) elimination is particularly important in diving as unconsciousness can result from excessive arterial CO_2 tension (PCO_2), known as hypercapnia. Key factors that control CO_2 elimination in rebreather diving include immersion, exercise, gas density, ventilation rate, control of breathing, CO_2 scrubber failure, and breathing apparatus design. These factors are reviewed and a list of strategies for the avoidance of hypercapnia during diving is provided.

Keywords: closed-circuit, CO_2 retention, CO_2 scrubber, hypercapnia, static lung load

INTRODUCTION

Immersion, the use of an underwater breathing apparatus, and the breathing of gases at densities higher than air at 1.0 atm have important effects on respiratory function for all divers. These effects are potentially magnified for technical rebreather divers who venture deeper and may breathe very dense gas via complex rebreather devices. This paper will review respiratory issues of high relevance to rebreather divers. A much more detailed summary has been recently published (Doolette and Mitchell, 2011).

GAS EXCHANGE

The key goal of breathing is gas exchange: the oxygenation of blood and removal of carbon dioxide (CO_2) from blood as it passes through the lungs. Gas exchange occurs between gas in the lung alveoli and the blood flowing through the surrounding capillaries.

To put some numbers on this we must introduce the somewhat confusing unit of millimeters of mercury (mmHg) that is used to express physiological gas pressures, where 1.0 atm = 760 mmHg. Divers are familiar with simple calculations using Dalton's law to derive partial pressures. Thus, since oxygen constitutes 21 percent of air, its partial pressure in air at 1 atm in mmHg is 0.21 x 760 = 160 mmHg. In the alveoli, oxygen is both arriving and being removed into the blood, and the result of this dynamic process is that oxygen constitutes only about 13-14 percent of alveolar gas. In a healthy person breathing air at 1.0 atm, the alveolar PO_2 is around 90-100 mmHg. Although there is virtually no CO_2 in the inspired air, CO_2 moves from the blood into the alveolus such that the PCO_2 in the alveoli of a normal healthy person breathing air at 1.0 atm is about 40 mmHg.

One important point to understand is that the contact between the gas in the alveolus and the blood in the lung capillaries is so intimate that the pressures of gas in the alveolus and the blood equilibrate very quickly, and therefore, under most circumstances the partial pressure of gases in the blood leaving the alveolus (which ultimately becomes the arterial blood) are the same as the partial pressure of gases in the alveolus. This is summarized in diagrammatic form in Figure 1. In reality, the partial pressure of oxygen in arterial blood is slightly lower than you would predict from this diagram for a number of reasons that are unimportant to this discussion.

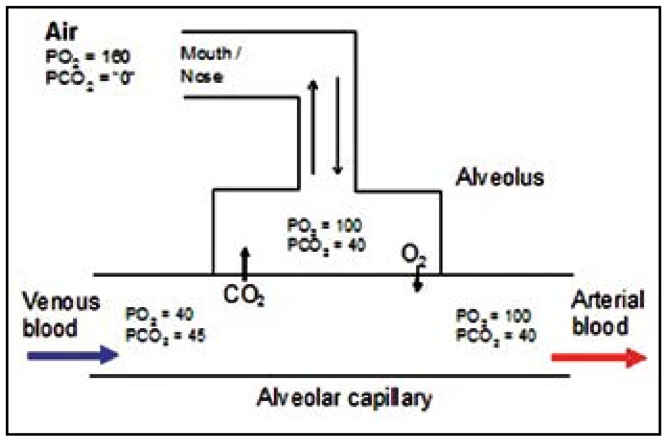


Figure 1. Partial pressures of oxygen and CO_2 at the mouth, in the alveolus, and in blood entering and leaving the alveolar capillaries. It is often assumed that the alveoli are flushed with "fresh air" with every breath. In fact, there is no complete "flushing" in the alveoli, and the composition of alveolar gas is determined by a complex and dynamic balance between the arrival of new gas down the airway and gas exchange with the blood. Partial pressures are measured in mmHg (see text).

DEPENDENCE OF GAS EXCHANGE ON VENTILATION

It is crucial to understand the critical dependence of CO_2 elimination on the amount of fresh gas moved in and out of the lungs ("ventilation"). Why single out CO_2 when common sense tells us that oxygen uptake must also be dependent on ventilation? While this is true, if the amount of oxygen in each breath is high, then fewer breaths are required to keep the arterial oxygen levels normal. This is relevant to technical divers who frequently breathe high partial pressures of oxygen.

Ignore diving for the moment and consider a healthy 70-kg (154-lb) adult at rest breathing 100 percent oxygen. The question is: What happens to the arterial oxygen and arterial CO_2 levels if he exhales normally and stops breathing for five minutes? A few more numbers are required to answer this adequately. First, the approximate volume of gas left in the lungs at the end of exhalation (the functional residual capacity) is 30 $mL \cdot kg^{-1}$, so if we assume that the lungs only contain oxygen, then there will be 30 $mL \cdot kg^{-1}$ x 70 kg = 2100 mL of oxygen in the lungs. Second, the approximate oxygen consumption for an adult at rest is about 300 $mL \cdot min^{-1}$. Thus, in theory, there is enough oxygen in the lungs to keep this person well oxygenated for 2100 mL ÷ 300 $mL \cdot min^{-1}$ = 7 minutes. Most important, the levels of oxygen in the arterial blood will not be disturbed at all for most of this time. We can conclude that in this scenario it would be possible not to breathe for five minutes with no deficit in oxygenation of the blood.

In contrast, from the moment this subject stops breathing, CO_2 will begin to accumulate. It will be still delivered to the alveoli in the venous blood, but with no ventilation it will not be removed from the alveoli. It is analogous to a circular conveyor (Figure 2) where one person puts objects on and another takes them off. In this case, if the lungs taking CO_2 off the conveyor stop working and the tissues continue to put CO_2 on, then the amount of CO_2 on the conveyor (in the blood) will increase.

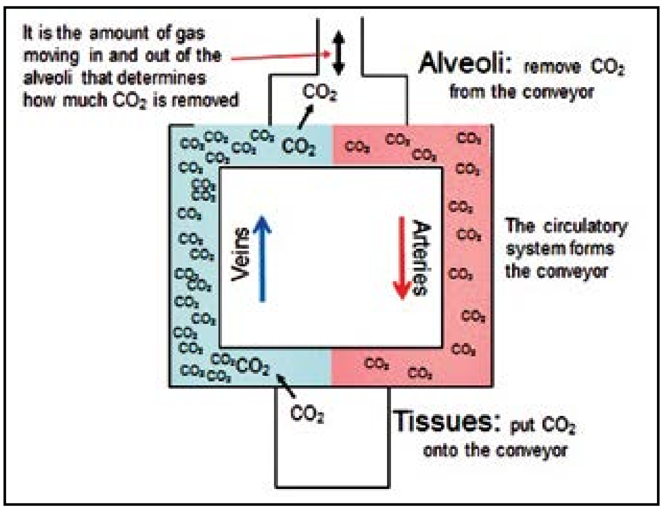


Figure 2. "Circular conveyor belt model" of CO_2 elimination. The "conveyor" (circulation) constantly moves clockwise. The tissues put CO_2 on the conveyor, and the alveoli remove it. Note that some is left in the arterial blood, and this is normal. As long as the alveoli remove CO_2 from the "conveyor" at the same rate that the tissues put it on, the net amount of CO_2 on the conveyor will not change. But if there is an imbalance in activity at the tissues and alveoli, then the amount of CO_2 on the conveyor will change. The removal of CO_2 by the alveoli is totally dependent on the amount of fresh gas moving in and out of the lungs. Thus, if a diver holds his breath or reduces his breathing relative to CO_2 production in the tissues, then CO_2 will rise.

The point of this discussion is to illustrate that when inspired and alveolar PO_2 is high and there are large volumes of oxygen in the lung relative to metabolic needs (as is commonly the case in technical diving), a diver could ventilate a lot less than he does and still remain well oxygenated. However, from the moment ventilation falls below that required to maintain alveolar (and therefore arterial) PCO_2 at the desired level, then the arterial PCO_2 will begin to rise. It does not require the diver to actually stop breathing as in the illustrative example above; a period of reduced breathing resulting in removal of less CO_2 than the tissues are producing (i.e., hypoventilation) will cause CO_2 accumulation (just a bit more slowly). This is a problem because, as most technical divers know, arterial CO_2 levels do not have to rise much for the adverse effects to begin.

This is all highly relevant because there are multiple reasons why a diver might hypoventilate, thus allowing toxic levels of CO_2 to accumulate. This point is poorly appreciated by many divers, especially rebreather divers, who immediately link CO_2 toxicity with scrubber failure and CO_2 rebreathing. Scrubber failure and rebreathing of CO_2 can certainly cause CO_2 toxicity, but, as this discussion illustrates, it is not the only (or even the most common) cause. Merely failing to breathe enough is often to blame!

HOW IS BREATHING CONTROLLED?

Control of breathing is a complex and incompletely understood area of physiology. However, some aspects that are relevant to diving and relatively well understood are discussed here.

Control of breathing arises from the brainstem. There is a center that acts as a respiratory "rhythm generator," instigating periodic inspirations and maintaining a basic breathing rhythm. This center receives modifying input from a variety of other centers in the brain and brainstem. The most important of these comes from specialized nerve cells or "receptors" that lie nearby, also in the brainstem. These receptors are very sensitive to the hydrogen ion concentration (which we measure using the pH scale) of their surrounding tissues. Carbon dioxide is free to diffuse from the arterial blood into these tissues and the nearby cerebrospinal fluid. Here, it rapidly reacts with water to form bicarbonate and hydrogen ion, and the consequent increase in the concentration of hydrogen ions is sensed by the receptors. This is a potent breathing stimulus. If all of this sounds a bit complex, then it can be summarized simply: When CO_2 rises, breathing will be stimulated, and when CO_2 falls, the drive to breathe will be reduced. This is entirely logical given the preceding discussion of the importance of breathing for maintaining CO_2 levels in the blood.

There are several variable characteristics of this control system that are relevant to diving. First, there appear to be differences between individuals in the degree to which breathing increases in response to an increase in blood CO_2 (we refer to this as their "sensitivity to CO_2") (Lanphier, 1955). These differences may be innate or acquired; in respect to the latter, there is some evidence that diving may reduce sensitivity to CO_2. Second, it seems that if maintenance of CO_2 requires more work than is involved in normal air breathing, the respiratory control center in some individuals seems content to allow the CO_2 to rise somewhat rather than perform the work (i.e., breathing) required to lower it again (Poon, 1989). This is crucially important because there are many things in diving that potentially increase the work of breathing. Finally, a high PO_2 and high PN_2 (both of which are encountered in diving) may decrease sensitivity to rising CO_2 (Linnersson and Hesser, 1978) All of these factors potentially contribute to an increase in arterial CO_2 during diving, and we will return to this issue later.

WHAT ARE THE EFFECTS OF IMMERSION, DIVING EQUIPMENT, AND INCREASING GAS DENSITY ON RESPIRATORY FUNCTION?

Immersion

Immersion, even in shallow water, causes a number of important physiological changes that have an impact on respiratory system function.

Redistribution of blood volume

Irrespective of a diver's orientation in the water, there is a centralization of blood volume because of peripheral vasoconstriction and the loss of the gravitational effect that usually results in pooling of blood in the dependent veins (especially in the legs when we are upright). This blood volume shift results in a relative (though tolerable) congestion of the distensible pulmonary circulation with blood. This makes the lungs a little "stiffer," which may increase the work required to maintain the same level of lung ventilation.

Static lung load (SLL)

When immersed, the body is exposed to a vertical pressure gradient in the water column. Simply put, and as every diver knows, pressure increases with depth. This sets up an important interaction between diver and breathing apparatus.

Consider a rebreather diver with a front-mounted counterlung lying horizontally in the water. The diver's airways are in continuity with the counterlung, which lies slightly deeper and therefore at higher pressure than the lungs. This means that the lung airways are subject to a positive pressure equal to the vertical height of the water column between counterlung and lung. We refer to this as a positive static lung load (SLL) (Figure 3). The diver will notice that inhalation seems easier because it is assisted by the SLL, whereas exhalation requires extra effort because it is against the SLL. The reverse would be true for a horizontal diver wearing a back-mounted counterlung. The resulting negative SLL would make inhalation seem harder and exhalation seem easier. These effects are not limited to rebreather divers. The same phenomenon arises when there is a vertical differential between an open-circuit demand valve (which supplies gas at ambient pressure) and the lungs (Figure 3). Because the demand valve is higher than the lungs, the gas is supplied at a slightly lower pressure than that to which the lungs are exposed, thus constituting a negative SLL.

It would seem logical to assume that the opposite effects of an SLL on the effort of inspiration and expiration (as described above) would somehow "balance each other out" and that overall it would be of negligible importance. Unfortunately, this does not seem to be the case. In fact, the physiological significance of an SLL is quite complex.

A negative SLL further enhances the redistribution of blood into the very distensible vessels of the chest cavity (described above in relation to redistribution of blood volume). This increased congestion of the lung circulation with blood causes further stiffening of the lung tissue, and the volume of gas left in the lungs at the end of a normal expiration falls. This means that at the start of an inspiration the lungs are at a lower volume and the airways are narrower, thus increasing the resistance to gas flow (see later). Not surprisingly, there are data that demonstrate both an increase in the work of breathing and an increase in the subjective sense of breathlessness when a negative SLL is imposed (Taylor and Morrison, 1989). Positive SLLs are less commonly encountered but can also be disadvantageous at extremes. Nevertheless, there are some data to suggest that divers are most comfortable and work is best facilitated at a slightly positive SLL (Lanphier, 1989).

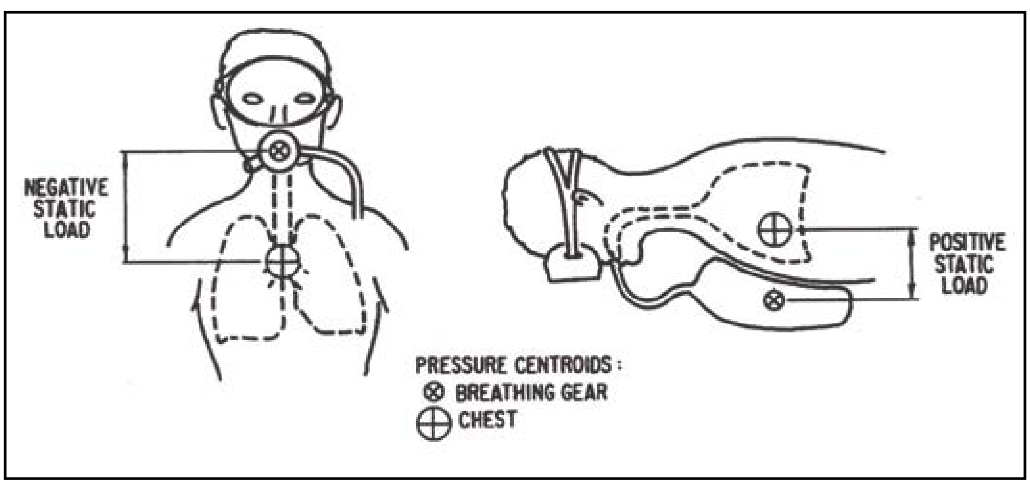


Figure 3. Diagrammatic representation of static lung load. (Reproduced from Figure 1 in Warkander et al., 1989).

There has been much discussion on how to compensate for SLL during diving, but there are significant practical obstacles, and virtually all diving is undertaken with uncompensated equipment. In this regard, it is important to maintain some perspective on the problem represented by SLLs. This phenomenon is part of everyday diving, and most dives do not result in overt respiratory discomfort let alone accidents resulting from respiratory problems. It follows that under normal circumstances the physiological challenge of a modest SLL can be met and managed without problems. However, the issue is worthy of note as one of several potential contributors to respiratory difficulties (other examples being hard work, high equipment breathing resistance, and denser gas) that, should they become relevant simultaneously, might result in difficulty maintaining adequate lung ventilation.

Diving equipment

The use of diving equipment will almost invariably impose an extra resistance to breathing that would not be present if the diver was simply breathing through his own airway. This is another potential contributor to increased work of breathing, and it is universally agreed that minimization of equipment-related breathing resistance is desirable. At the same time, it is acknowledged that some resistance is inevitable. For example, the CO_2 scrubber canister in a rebreather will always cause some resistance to gas flow.

Since the order of components in a rebreather can be varied, there has been investigation of where their associated resistance might be best tolerated. Warkander et al. (2001) separated equipment-related breathing resistance into its inspiratory and expiratory components and showed that divers react to an imposed resistance by prolonging the phase (inspiration or expiration) that is loaded. More important, they showed that expiratory resistance seems better tolerated in terms of both the divers' subjective impressions of discomfort and objective respiratory parameters. This suggests, for example, that rebreather CO_2 scrubbers should be placed on the expiratory side of the counterlung and not the inspiratory side.

Increasing gas density

The density of any given breathing gas increases linearly with depth. Technical divers substitute helium for nitrogen in gas mixes for deeper diving, which substantially reduces density. Nevertheless, at the depth targets being set by some extreme exponents, gas density still increases significantly despite the use of helium. For example, on David Shaw's widely reported fatal dive, the use of trimix 4:82 (4 percent oxygen, 82 percent He, balance N_2) at 264 mfw (866 ffw) equated approximately to air at 70 m (230 ft; 8 ATA) in terms of gas density (Mitchell et al., 2007).

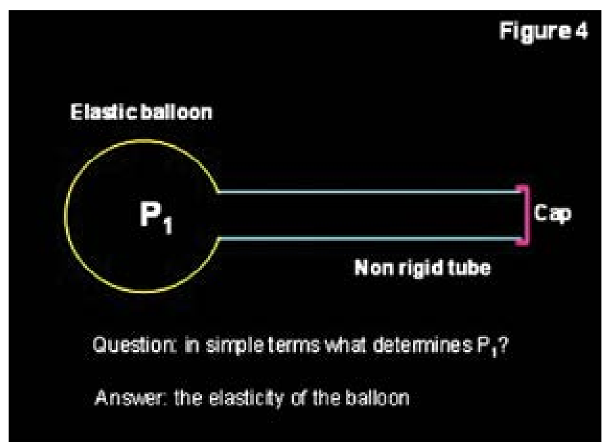
Dense gas has a significant impact on respiratory function primarily by increasing resistance to flow through airways and thereby increasing work of breathing and limiting ventilatory performance. Indeed, if you ask a subject to ventilate as hard as he can while breathing air at the modest depth of 30 m (130 ft; 4 ATA), the maximum volume he can shift over a minute is only half of that at the surface. Most of this reduction is attributed to the increase in gas density.

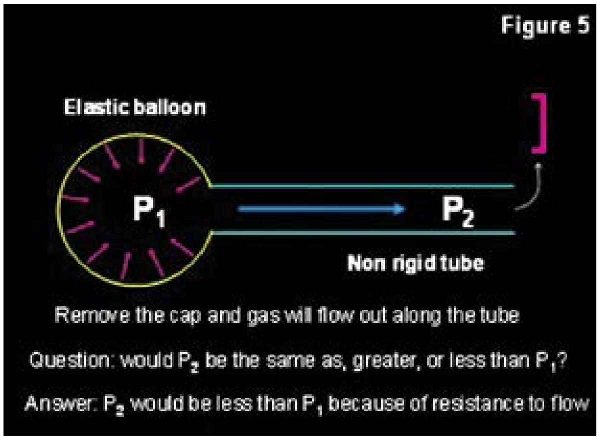
Work and exercise requires gas exchange, and gas exchange (particularly CO_2 elimination) requires ventilation, as discussed earlier. The clear implication of progressively limited ventilation with increasing gas density is that as depth increases the diver's work capacity decreases. Indeed, it is plausible that the maximum depth that technical divers can visit may ultimately be determined by their ability to cope with the work of breathing, let alone any other work such as swimming. Even at more modest depths, it is possible that if the work of breathing is high, the gas is dense and significant exercise is attempted, divers may get themselves into a situation where they cannot ventilate enough to keep their CO_2 at normal levels. We refer to this as respiratory failure.

Dynamic airway compression, effort-independent exhalation and respiratory failure

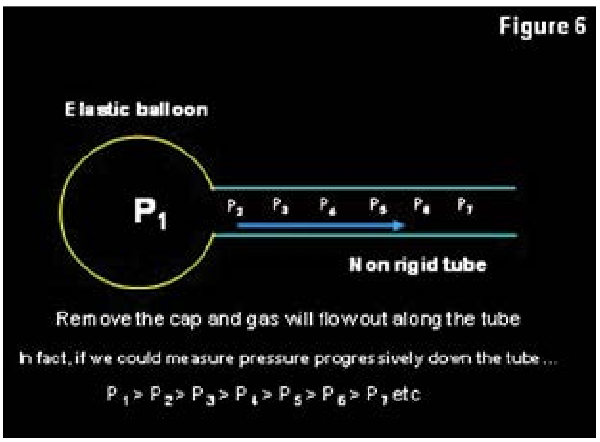
Why does increasing gas density cause such a significant reduction in the ability to move gas in and out of the lungs? At least part of the explanation is a phenomenon known as "dynamic airway compression." This complicated physiological event is explained in a step-wise simple manner below. Follow the series of diagrams (Figures 4-12) through in sequence along with the explanatory notes.

Consider a non-rigid tube with an inflated balloon on one end and a cap over the other (Figure 4). The balloon will be generating a pressure that is determined by its elasticity.

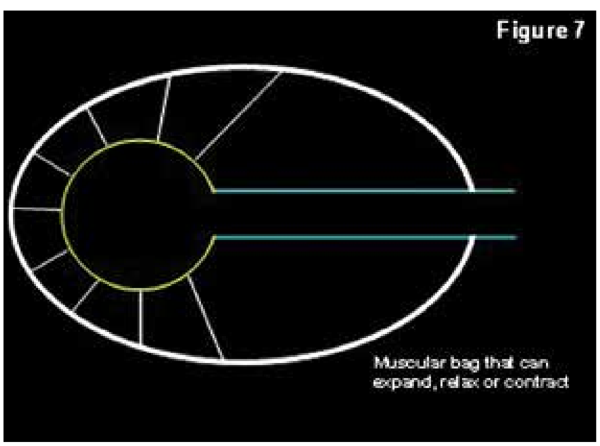




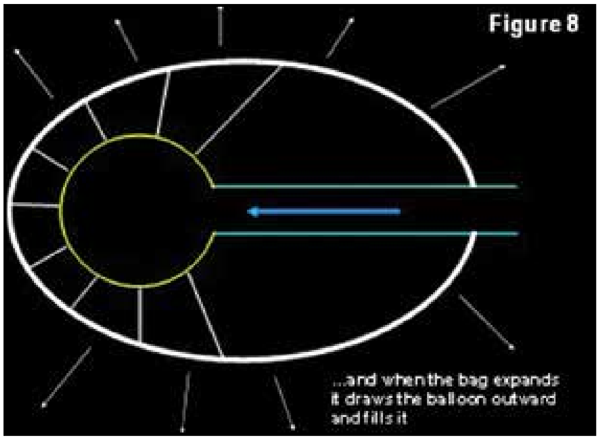
Now, the cap is removed from the tube, and the elastic balloon contracts, forcing air out along the tube (Figure 5). Because of resistance to flow, the pressure of gas driving flow through the tube will fall the further along the tube you go.



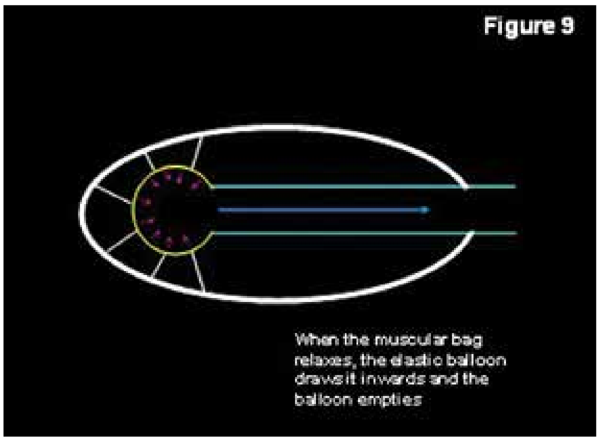
Indeed, if we could measure the pressure at many points along the tube (Figure 6) we would find a progressive fall in pressure. A key point is that ***if the gas inside the balloon were denser, then the pressure drop along the tube would occur more quickly*** because resistance would be greater.



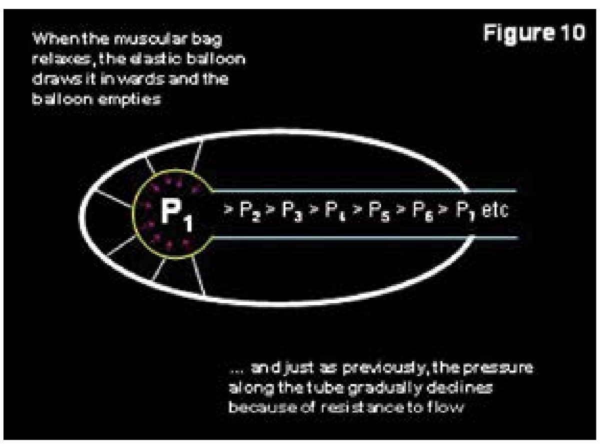
Now we place this balloon and tube structure inside a muscular bag that can expand, relax, or contract. The balloon is tethered to the bag so it is responsive to these movements (Figure 7). This is a "single alveolus" model of the lung, where the bag represents the chest wall and diaphragm, the balloon is the alveolus, and the tube is the airway. Obviously, the real lung has millions of alveoli.



When the muscular bag expands (Figure 8), the balloon is stretched outward and gas is drawn inward.



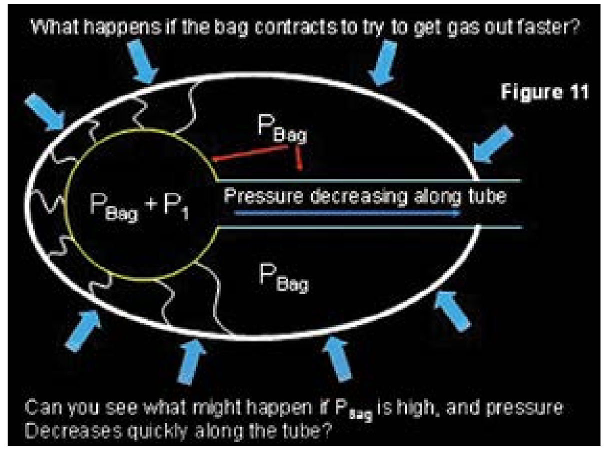
When the muscular bag relaxes, the elastic balloon draws it inward, and the gas in the balloon moves outward along the tube (Figure 9). Note that the bag only has to relax, and the elasticity of the balloon does the work, just as is the case during a normal exhalation in a real lung.



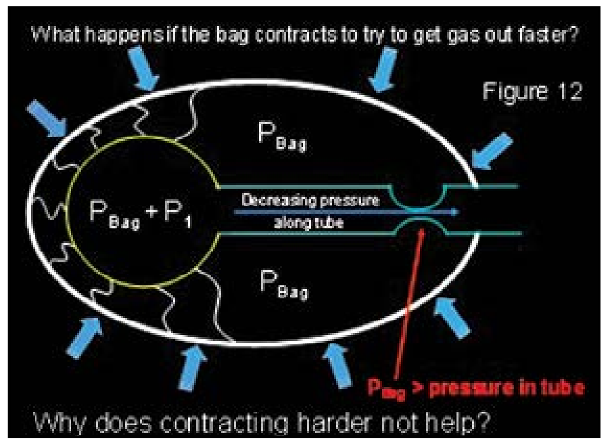
And just as previously, as gas flows out along the tube, the pressure gradually declines because of resistance to flow (Figure 10).

Question: What happens if the bag contracts hard to try to force gas out of the balloon more quickly as in a forced exhalation during exercise?

There is now a positive pressure in the bag (P_{bag}). Thus, the pressure forcing gas out of the balloon is now P_1 (the elasticity of the balloon) plus P_{bag}. (Figure 11). However, the positive pressure in the bag is also applied to the outside of the distensible tube (airway) leading out of the balloon. **What will happen if the pressure in the bag is high and pressure decreases quickly along the tube?**



If the pressure in the tube drops quickly as gas passes out, then there may come a point where P_{bag} exceeds the pressure in the tube, and the tube will tend to collapse (Figure 12). **This would be more likely to happen if the gas in the balloon was dense and the pressure drop along the tube was consequently greater.**



The phenomenon illustrated in Figure 12 is "dynamic airway compression." Once this occurs, no amount of extra expiratory effort will increase the flow of gas out of the balloon. This is because any extra pressure created inside the bag is applied to both the balloon and to the outside of the distensible tube, thus there is no net gain. Exhalation under these conditions is thus said to be "effort independent." Effort-independent exhalation can occur in everyday life. In fact, it is seen during a forced exhalation in normal subjects breathing air at 1.0 ATA. But when breathing air at normal density, it occurs at such high flow rates that it does not really matter. The exercising person breathing air at 1.0 ATA can still rapidly shift huge volumes of gas in and out of the lungs despite the presence of effort-independent exhalation.

The problem in diving is that effort-independent exhalation will occur at much lower flow rates when a denser gas is breathed because the pressure drop along a tube is much greater. Thus, Wood and Bryan demonstrated that effort-independent exhalation was almost encountered during normal resting breathing when breathing air at 10 ATA (Wood, 1969). Put in more practical terms, if a diver breathing air at 10 ATA tried to do much more than normal quiet breathing, he would have difficulty increasing his ventilation no matter how hard he tried. While air at 10 ATA seems farfetched, it is not difficult to imagine gas mixes of equivalent density being used at extreme depth given the rate at which technical diving is progressing. Indeed, as previously mentioned, David Shaw's trimix on his 264-m (866-ft) dive had an equivalent density to air at 8 ATA (Mitchell et al., 2007).

Perhaps most frightening of all, the phenomenon of dynamic airway compression sets up the scenario described as a major contributor to David Shaw's death (Mitchell et al., 2007). Thus, a diver undertakes exercise during a very deep dive, breathing gas at high density. Attempts to increase ventilation to keep CO_2 at normal levels are unsuccessful because of dynamic airway compression. Increasing arterial CO_2 drives the diver to breathe harder, but exhalation is effort independent, and the extra effort fails to produce the increase in ventilation required to lower the arterial CO_2. In fact, the extra effort is just wasted work and only serves to produce more CO_2. The diver enters a vicious spiral in which increasing CO_2 drives greater respiratory effort, which just produces more CO_2. This will ultimately result in respiratory muscle exhaustion, rapidly rising CO_2, and CO_2 narcosis leading to unconsciousness. This scenario was predicted by Wood (Wood and Bryan, 1969) and may well have been demonstrated in a practical sense by both the Shaw accident (Mitchell et al., 2007) and other accidents caused by hypercapnia.

PUTTING IT TOGETHER: HOW DOES HYPERCAPNIA OCCUR?

Hypercapnia is a potentially dangerous state of excessive arterial PCO_2. In its early stages hypercapnia may produce a headache and mild shortness of breath. At more severe levels it can produce debilitating shortness of breath, disorientation, impaired cognition, and ultimately unconsciousness. Hypercapnia also enhances the effect of nitrogen narcosis and increases the risk of oxygen toxicity. Most of the mechanisms that might contribute to its occurrence have been mentioned in the previous sections of this paper, but it is such an important subject that it justifies an integrated summary.

As implied earlier, in the absence of CO_2 rebreathing (see later) hypercapnia is always due to inadequate lung ventilation relative to CO_2 production. Thus, anything that increases CO_2 production or causes inadequate ventilation will favor an increase in arterial CO_2. We refer to this as CO_2 retention.

Causes of inadequate ventilation and CO_2 retention

1. *Altered respiratory control with reduced sensitivity to CO_2*
We have already mentioned several mechanisms by which the control of breathing in the brainstem may become less sensitive to rising CO_2 — that is, it fails to drive an adequate increase in ventilation to reduce rising levels of CO_2.

a. Individual variability: Some individuals appear to be less sensitive to CO_2. That is, arterial CO_2 can rise further before a significant stimulus to breathe harder is developed. The term "CO_2 retainer" is sometimes used to describe such individuals. There is some evidence that this desensitization to CO_2 can be acquired as a result of diving (Lanphier, 1955). A consequent small increase in arterial CO_2 that does not produce any symptoms is not, of itself, necessarily harmful. However, the main concern is that such individuals may be at higher risk of oxygen toxicity and more susceptible to the effects of nitrogen narcosis.
b. Increases in work of breathing: As previously mentioned there is a tendency for the respiratory controller to reduce its sensitivity to CO_2 when work of breathing increases (Poon, 1989). Put another way, the respiratory controller will tolerate higher levels of CO_2 if an increase in work would be required to eliminate it. Although there may also be some individual variation in this tendency, this is relevant to all divers because, as previously discussed, the work of breathing virtually always increases during diving.
c. Higher pressures of oxygen and nitrogen: There is evidence that the sensitivity of the respiratory controller to CO_2 falls in the presence of hyperoxia or when high pressures of nitrogen are breathed (Linnarsson and Hesser, 1978).

2. *Conscious overriding of the drive to breathe*
To a point, divers are able to consciously override the urge to increase ventilation. This is sometimes invoked as a strategy to conserve gas during open-circuit diving and has in the past been referred to as "skip breathing." The earlier discussion of gas exchange and dependency of CO_2 elimination on ventilation should make it clear why skip breathing with an elevated inspired PO_2 would be fine from an oxygenation point of view but will result in CO_2 retention. This is a dangerous practice and should be discouraged.

3. *Adoption of a disadvantageous breathing pattern*
There is about 150 mL of gas in the lung airways, the trachea and mouth at the end of an exhalation. This is gas that has already been in the alveoli, and thus it has CO_2 in it. Most diving equipment mouthpieces add another 50 mL to this so-called "dead-space" gas. For arguments sake, assume that a diver has about 200 mL of dead space gas. This gas will be the first gas inhaled back into the alveoli at the start of the next breath. Because it already contains CO_2, this 200 mL represents wasted ventilation in terms of CO_2 elimination.

Under normal circumstances, this should not matter much. The normal tidal volume is about 10 $mL{\cdot}kg^{-1}$, so for a 70-kg (154-lb) adult it is approximately 700 mL. Assuming 200 mL of dead space for a diver, this means that 500 mL of each breath is fresh gas. However, problems can arise if a diver adopts a rapid breathing pattern with low tidal volumes. If the tidal volume were to drop to 400 mL, then dead-space gas represents half of each breath. It is for this reason that divers are encouraged to adopt a pattern of slower deep breaths in preference to a pattern of fast shallow breaths.

4. *Respiratory failure*
This term implies that ventilation is inadequate despite a strong drive to breathe. The main contributors to this scenario in diving are the extra breathing resistance imposed by the underwater breathing apparatus, the breathing of a dense gas and the physiological consequences of this (such as dynamic airway compression at low flow rates), and, potentially, respiratory muscle exhaustion as a terminal event. These concepts have been discussed in detail earlier and so will not be amplified here. True respiratory failure is probably a rare event, especially in more modest depths and during use of low-density gases.

Causes of increased CO_2 production

Fundamentally, the only cause of increased CO_2 production is increased work. Thus, exercise results in production of more CO_2, whereas rest should reduce it. The only point that requires emphasis in regard to diving is that breathing itself requires work and results in production of CO_2. When a diver breathes dense gas and/or if the underwater breathing apparatus imposes significant degrees of resistance, then the work of breathing can be a significant contributor to CO_2 production and in some scenarios may be virtually all that the diver is capable of doing.

CO_2 rebreathing

Rebreather divers should note that this extensive discussion of mechanisms of hypercapnia has taken place to this point in the absence of any mention of CO_2 scrubber failure. Yet the potential for hypercapnia because of CO_2 retention as discussed here is often ignored in the analysis of hypercapnia events during rebreather diving, where most commentators immediately target scrubber failure as the culprit.

This is not to say that scrubber failure is unimportant, for it certainly is another potential cause of hypercapnia. If there is scrubber failure and CO_2 is inspired, then the removal of CO_2 from the body by ventilation becomes much less efficient. If the amount of inhaled CO_2 is small, the arterial CO_2 may be kept normal by an increase in ventilation, but with a larger amount of inspired CO_2 the arterial CO_2 may continue to rise no matter how hard the diver breathes.

Detecting hypercapnia

Hypercapnia can be detected by recognizing the early symptoms of anxiety, headache and shortness of breath, but unfortunately, in at least some cases, by the time these symptoms are recognized the diver is very close to being incapacitated. Early detection of hypercapnia using instruments is therefore an area of emerging interest.

CO_2 in a mix of gases can be detected and measured using its unique absorbance of infrared light. There are engineering challenges relating to the use of these sensors given the temperature fluctuations, gas mixes, and humidity in the rebreather environment, but there are now CO_2 sensors that appear to work.

Such sensors are used every day during anesthesia for patients undergoing surgery. The anesthetist controls the patient's breathing using a mechanical ventilator. To ensure that ventilation is adequate to keep the CO_2 normal in a patient who is not controlling his own breathing, the arterial CO_2 must be measured. With reference to Figure 1, it should be noted once again that the CO_2 levels in the alveoli and the arterial blood are in equilibrium. It follows that if the PCO_2 in the gas coming from the alveoli in the very last part of the exhalation is measured as it is breathed out, then this will represent a reasonably accurate measure of the PCO_2 in the arterial blood. This is called measuring the "end-tidal CO_2."

The CO_2 sensor and its power supply are quite bulky, so in anesthesia a very small-diameter plastic sampling tube is plumbed into the breathing circuit, effectively at the patient's mouth. A pump constantly draws gas from the circuit to the analyzer at a fairly high flow rate to give fast response times. In this way, during inhalation the CO_2 in the inspired gas is measured. Anesthesia circuits have a CO_2 scrubber just like a rebreather, so the inhaled CO_2 should be zero. A second reading is taken at the very end of exhalation to give the end-tidal CO_2, which as previously discussed gives an adequate indication of the arterial CO_2.

It is crucial to understand the functional difference between these two measurements. Monitoring of the inhaled gas detects CO_2 breaking through the scrubber and warns the diver that he is therefore rebreathing CO_2. This is obviously useful and potentially important. However, measuring only the inhaled CO_2 means that the diver could become severely hypercapnic because of inadequate breathing (CO_2 retention) without any warning from the CO_2 sensor. If we measure exhaled CO_2 in a manner that gives an accurate end-tidal value, then it tells us whether the diver is hypercapnic for any reason (be it CO_2 rebreathing or retention).

Plugging the sampling line into the circuit at the mouth is therefore ideal for two reasons. First, it allows sampling both the inhaled gas and exhaled gas and measurement of CO_2 during both inhalation (detects scrubber breakthrough) and exhalation (detects hypercapnia from any cause). Second, by sampling at the mouth, we virtually guarantee that no dead-space gas in the mouthpiece and airways is expelled into the exhale hose before we make our end-tidal CO_2 measurement. This is important. As previously discussed, dead-space gas does not participate in gas exchange and at the end of inhalation is thus essentially the same composition as inspired gas and contains no CO_2. During exhalation we do not want this gas to contaminate our end-tidal CO_2 measurement because it would artificially lower the measured CO_2. By sampling at the mouth and waiting until the end of the exhalation to make the end-tidal measurement, we can be virtually guaranteed that this dead-space gas has disappeared into the exhale hose by the time the measurement is made.

CO_2 monitoring in rebreathers

Engineers have miniaturized the CO_2 sensors, but at this time they are still too bulky to fit into the mouthpiece of a rebreather. Moreover, a pump system for sampling gas from the mouthpiece via a fine tube to a sensor located elsewhere seems impractical; perhaps because it would be too power hungry for diving applications. What it adds up to is that we have some difficult choices in deciding where to place our CO_2 sensors.

One option is to put the sensor on the inhale limb of the rebreather circuit. The Sentinel (VR Technology, Ltd.) and others in the near future have this feature. This will tell the diver if CO_2 is breaking through the scrubber. It is obviously useful information, and the quantitative aspect is less important. In other words, it is less critical in this application that the sensor is highly accurate. The crucial piece of information is the presence or absence of CO_2; the exact inspired PCO_2 is less important (though still nice to know). For completeness, and in relation to CO_2 breakthrough monitoring, the use of thermal profile monitors in the scrubber should be mentioned. These devices do not detect CO_2 as such but rather indicate both the progress of the exothermic reaction front through the canister and the prevailing reaction activity throughout the material. They give an indication of the remaining scrubber absorbing capacity and if properly interpreted in context can provide warning of impending CO_2 breakthrough.

It should be clear from the previous discussion that a CO_2 sensor on the inhale limb provides no information about what is going on inside the diver. As discussed, CO_2 toxicity can occur because of retained CO_2. The only way to detect increasing CO_2 (from any cause, be it retention or rebreathing) in the diver is to measure CO_2 in the expired gas at the end of exhalation. There has been one proposal to put a sensor at the end of the exhale hose for this purpose, but placement of the sensor here risks mixing of dead-space gas with the alveolar gas in the exhale hose prior to the end-tidal measurement being made, and a consequent underestimation of the true end-tidal CO_2. At the time of writing (July 2012), end-tidal CO_2 measurement is not available in any rebreather.

Preventing and treating hypercapnia

A relatively simple list of strategies for the avoidance of hypercapnia during diving can be constructed from perusing the list of its causes. Thus, one might aim to:

1. Ensure that the underwater breathing apparatus used is optimally maintained and configured to reduce breathing resistance.
2. Choose a bottom mix gas with low density, and make this a priority over other considerations for very deep dives where significant exercise is anticipated.
3. Avoid significant exercise if possible on any deep dive.
4. Adopt a breathing pattern that is slow and deep rather than fast and shallow.
5. Never intentionally resist the urge to breathe or "skip breathe."
6. Stay physically fit, which might help avoid respiratory muscle exhaustion.
7. Discard scrubber material before its predicted "end of life," and always pack and install the scrubber meticulously.

In terms of treating hypercapnia, the time-honored advice for an out-of-breath diver to "stop, breathe deeply, and rest" remains valid but should be appended with "… as soon as you feel symptoms of hypercapnia," because it is often not followed until it is too late by highly motivated technical divers intent on completing a task or achieving a goal. The period of rest should be used to review options to favorably modify the situation. A quick review of the breathing equipment may be rewarding. For example, hypercapnia may be caused by the added breathing resistance of a partially closed cylinder or rebreather mouthpiece shut-off valves. Consideration can be given to lowering the density of the breathing gas by changing to a different mix (often not possible) or by decreasing the depth.

Rebreather divers are taught to bailout to an open-circuit gas supply in the event of hypercapnia because of the possibility that the problem is caused by failure of the CO_2 scrubber. This is valid advice that should be followed, but several cautionary points arise. First, if the problem is caused by CO_2 retention rather than scrubber failure, then bailing out is unlikely to help unless the work of breathing is actually lowered by changing to an open-circuit regulator. Indeed, if the regulator is poorly tuned it could make the problem worse. Second, many rebreather divers have reported extreme difficulty in removing their rebreather mouthpiece to facilitate a change to open-circuit while affected by CO_2-induced breathlessness. This illustrates the advantage of a bailout valve that allows access to open-circuit gas without removing the rebreather mouthpiece. Finally, the gas consumption will be extremely high when a breathless rebreather diver changes to open-circuit, especially if the change occurs in deep water. Small open-circuit supplies will not last very long.

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SEMICLOSED-CIRCUIT REBREATHERS

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ABSTRACT

Semiclosed-circuit rebreathers fill a multitude of diving roles from shallow-water recreational diving to deep cave diving and very deep saturation diving. They are preferred over electronic rebreathers in many applications due to their robust mechanical nature and dependability. As semiclosed-circuit rebreathers have shrunk in size, potential physiological issues have become more likely. Improved education and oxygen monitoring can offset the potential hazards of semiclosed-circuit rebreather diving.

Keywords: constant mass injection, constant volume injection, oxygen

INTRODUCTION

The Earth is a rebreather. It is a closed environment that supplies oxygen for all living things of the planet, with a natural scrubbing mechanism that prevents carbon dioxide (CO_2) from rising to dangerous levels. It needs no oxygen sensors or CO_2 monitors. Its batteries never run down, its consumables are never exhausted. You do not need a high IQ to use it, and you can be pretty careless about how you maintain it. The greatest and the least of us are kept alive with no effort on our part. It simply works.

For humans, the value and comfort of the Earth's rebreather is given up when we descend underwater. We have made good progress at diving underwater, gradually progressing from the strategy of diving spiders, carrying air on our backs.

Figure 1. Exhaled air collecting underneath the ice of the Ross Ice Shelf near McMurdo Station, Antarctica. Martin DJ Sayer, Cape Evans, Antarctica

One of the downsides of that crude but dependable method of diving is the exorbitant waste of air (Figure 1). One way to appreciate how much breathable air is wasted using open-circuit scuba is to dive underneath sheets of ice, where that exhausted air collects for all to see.

CONSERVING GAS — HISTORY

From a gas consumption standpoint, the most efficient type of underwater breathing apparatus is an electronically-controlled mixed-gas rebreather.

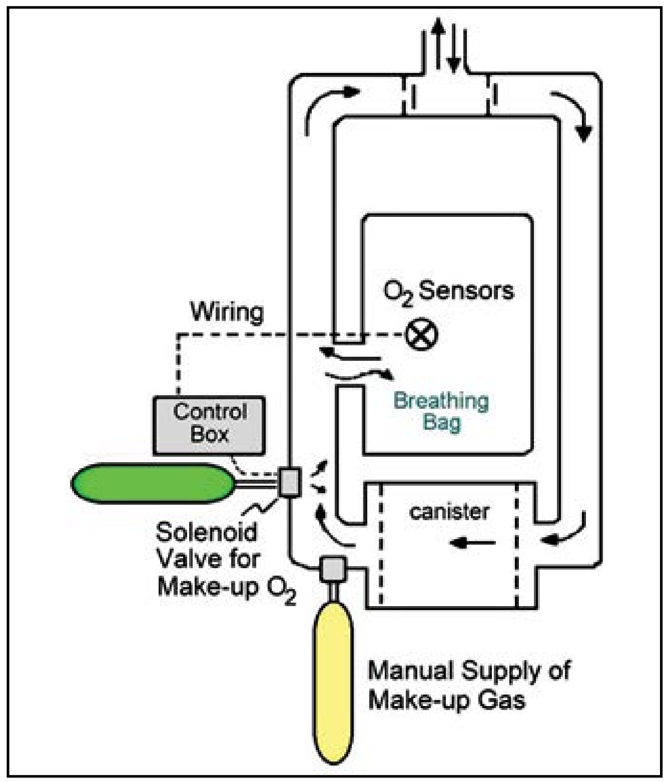

Figure 2. Schematic of an electronically-controlled mixed-gas rebreather.

However, some of the earliest and simplest rebreathers were not as complicated. Because of that mechanical simplicity those rebreathers were very unlikely to surprise the diver, although, as you will see, there are exceptions. I refer to those exceptions as the dark side of semiclosed-circuit rebreather diving.

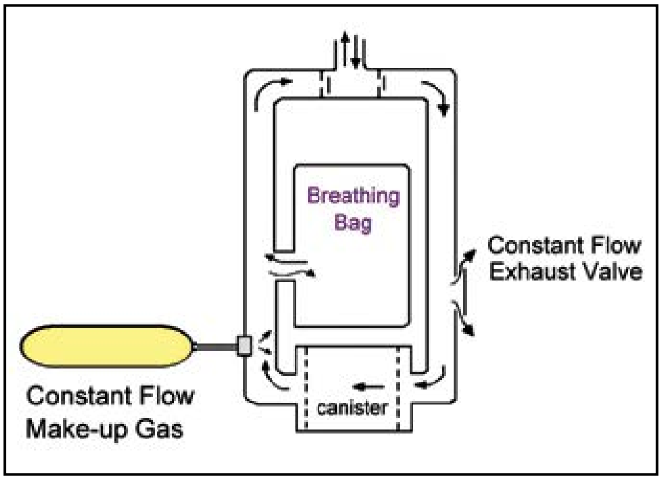

Figure 3. Schematic of the simplest mechanical semiclosed-circuit rebreather.

One of the simplest semiclosed-circuit rebreathers is based on a constant mass-flow of gas mix, a fixed percentage of nitrogen or helium in oxygen. Figures 4 and 5 are photos of the U.S. Navy's MK VI rebreather with over-the-shoulder dual breathing bags, introduced into the U.S. Navy inventory in 1963. It was originally used by explosive ordnance divers (EOD) due to its ability to quietly dive deep, where the mines are. It was modified for the U.S. Navy SEALAB saturation habitat program by being attached to a hookah, or umbilical.

Figure 4. Photo of the U.S. Navy MK VI semiclosed-circuit rebreather. U.S. Navy photo.

Figure 5. Back view of the U.S. Navy MK VI rebreather and a visitor to SEALAB II. U.S. Navy photo.

Figure 6. Photo of the Dräger FGT 1/D semiclosed-circuit rebreather. Photo by John R. Clarke.

The Flatus I and II, developed by Dr. Chris Lambertsen, were Navy prototypes of the mid-1950s, extensively tested at the U.S. Navy Experimental Diving Unit (NEDU). Dr. Lambertsen later confided that few within the Navy seemed to appreciate that Flatus was a medical term and was deemed appropriate in this case because of the rig's intermittent bubble exhaust, a feature of all semiclosed-circuit rebreathers.

In 1969, Germany's contribution to EOD diving was considerable, represented below by the sleek-looking Dräger FGT 1/D semiclosed-circuit rebreather, weighing 55 lb (25 kg). It shares some features in common with the much newer Dräger Dolphin.

Figure 7. Dräger FGT 1/D with fairing. Photo by John R. Clarke.

The deepest diving with these types of semiclosed underwater breathing apparatus (UBA) required the lowest oxygen concentration in the gas mix and the highest fresh gas flow rate, as shown in Table 1.

Table 1. Required fresh gas properties for various NATO mixes.

Gasmix NATO	% O_2	% N_2	Flow L/min	Work time (min)	Depth
B	60	40	6	150	24 m
C	40	60	8	110	24-42 m
D	32.5	67.5	13	70	42-54 m

THE SMALLER GENERATION

The vertical bars in Figure 8 show the relative size and weight of semiclosed-circuit rebreathers ranging from the MK VI to

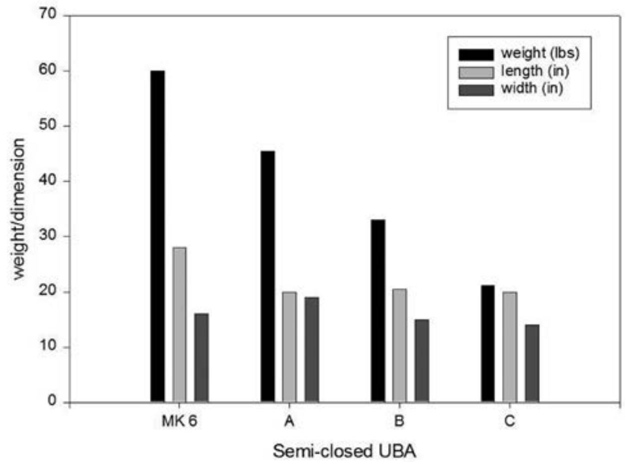

Figure 8. Comparison of weights and dimensions for early military and progressively smaller modern semiclosed-circuit rebreathers. John R. Clarke figure.

the now defunct Fieno Grand Bleu. The Fieno was a minuscule rig, weighing 12 lb (5.5 kg) and with an approximately 40-minute duration. It used a 40 percent O_2 mix, only safe for use down to 98 feet of seawater (fsw; 30 meters of seawater [msw]). Not surprisingly, advertisements for the Grand Bleu featured petite female divers.

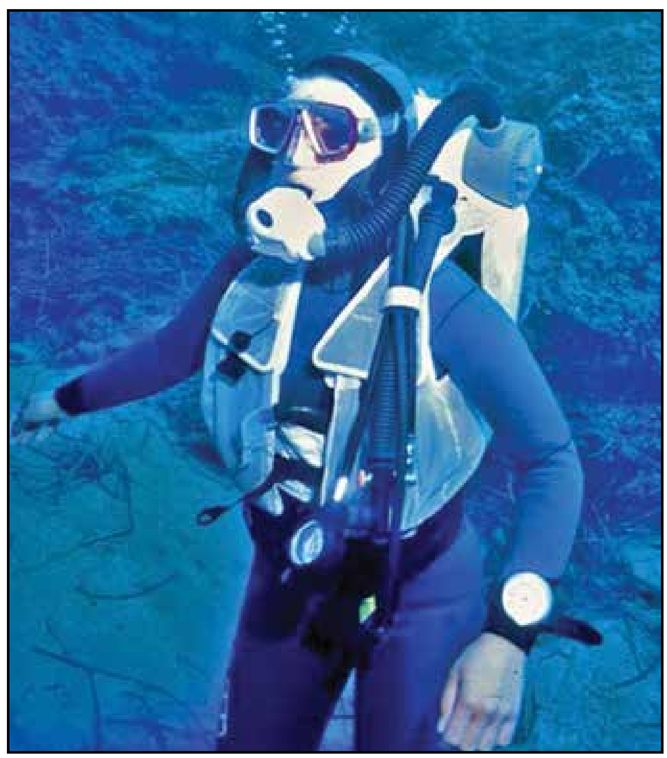

Figure 9. Fieno Grand Bleu. Photo by Fabio Bartolucci.

Which brings us to a modern marketing strategy with potentially serious complications. To reduce the size of a semiclosed-circuit rebreather you need gas bottles smaller than in the MK VI or the Dräger FGT. To get a reasonable dive duration out of smaller bottles you must reduce the so-called fresh gas flow rate.

To wit, the Grand Bleu had only a 2.0 $L\cdot min^{-1}$ fresh gas injection rate. Therein lies the rub.

When you reduce the size of a self-contained rebreather (meaning gas bottles are internal to the rebreather), you must reduce the size of the gas bottle. If you want the diver to have reasonable dive durations, then you must either greatly increase bottle pressure or you must reduce the steady flow gas rate that is being supplied to the diver.

The U.S. Navy did not fully appreciate the problem with that latter strategy until we came close to having diving accidents. At that time a semiclosed-circuit rebreather called the Dräger LAR7 was being used by U.S. Navy divers. The closest commercial version of this might be the Dolphin or its predecessor, the Atlantis. These units are relatively simple mechanically; a constant flow of premixed gas is delivered to the diver. Despite their mechanical simplicity, physiologically they are very complicated. What happens to divers is entirely dependent on what they are doing, how hard they are working, how deep they are diving, and what gas mix they are using. Inspired oxygen concentration can vary dramatically depending on dive conditions and diver work rate.

So while you have a seemingly bullet-proof small, simple rebreather, you may find yourself having physiological problems.

CONSTANT MASS INJECTION REBREATHERS

For constant mass injection rebreathers such as the MK VI, the Dräger FGT and the Grand Bleu, a relatively simple equation

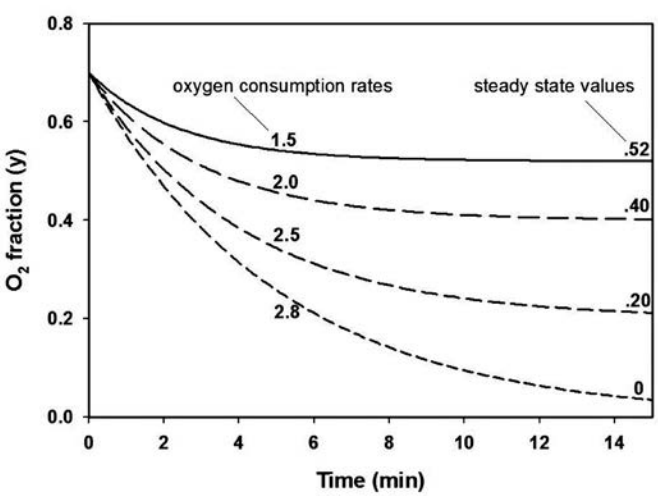

Figure 10. The typical time course of changes in oxygen fraction as a function of oxygen consumption in CMI rebreathers. John R. Clarke figure.

(Equation 1) relates the steady state fraction of inspired oxygen (FIO_2) to the fraction of oxygen in the injected fresh gas ($fractionO_2$), to the rate of fresh gas inflow (injectionRate), and to the diver's oxygen consumption ($\dot{V}O_2$, work rate) (Williams 1982; Clarke 1996).

$$FIO_2 = \frac{(fractionO_2 \cdot injectionRate) - \dot{V}O_2}{(injectionRate - \dot{V}O_2)}$$

Equation 1 is the steady-state solution to that more complete equation, and is identical to steady state equations offered for semiclosed UBA since at least the 1950s.

In the 1990s the NEDU solved the differential equations, describing the time course of those inspired oxygen changes (Clarke et al., 1996 a-c; Clarke, 1999b), and Figure 10 is the graph of the solutions.

Figure 11 shows how the old semiclosed-circuit rebreathers, with a high fresh gas injection rate, were relatively insensitive to diver work rate. Frankly, it was never a concern. However, for the new generation of reduced flow-rate rebreathers, the inspired oxygen fraction is highly sensitive to diver work rate.

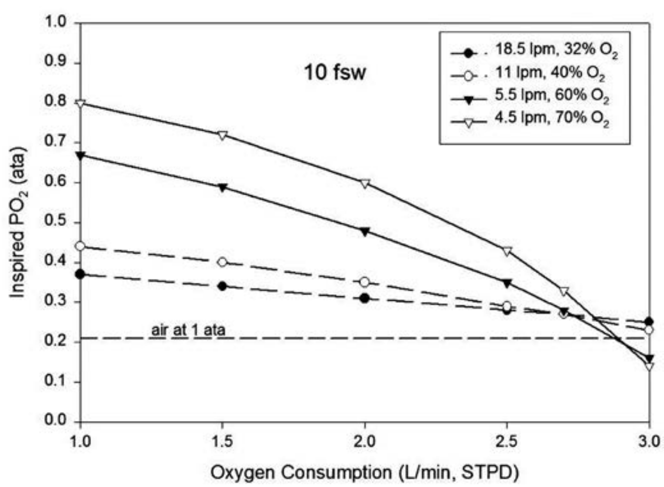

Figure 11. High flow-rate CMI rebreathers of the past were relatively insensitive to changes in diver oxygen consumption. John R. Clarke figure.

The first indication NEDU had that modern CMI devices were different from the older versions came when inspired oxygen fraction (FIO_2) was measured on six divers using the Dräger Nitrox (aka, LAR VII, Figure 12) in our 15-ft (5-m) deep test pool. The estimated steady-state values for an oxygen consumption of 0.5 $L\cdot min^{-1}$ is marked by the upper horizontal dashed line, and the expected value for a 2.0 $L\cdot min^{-1}$ oxygen consumption is indicated by the lower dashed line.

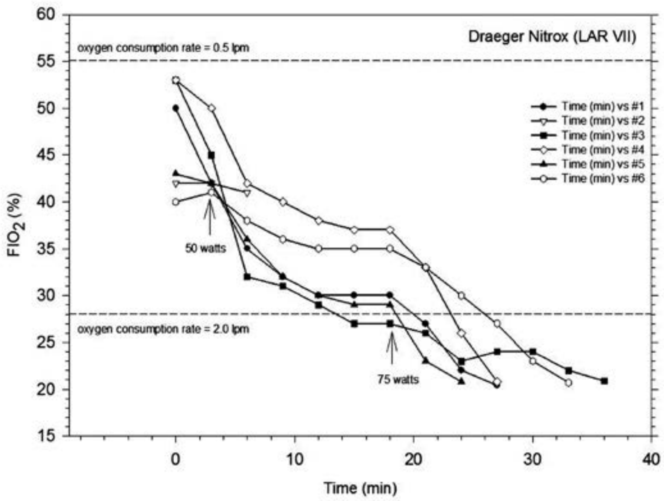

Figure 12. Response of a CMI rebreather to divers with unexpectedly high oxygen consumption rates. John R. Clarke figure.

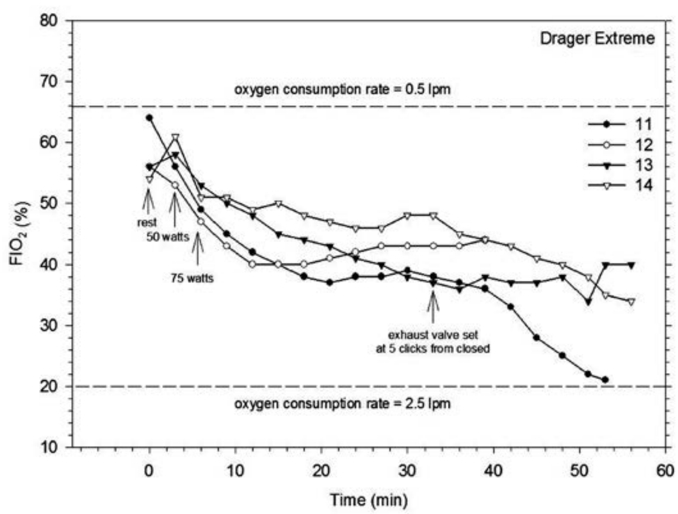

Figure 13. Effect of exhaust valve positioning on the bag oxygen concentration due to lack of activation of the demand-activated fresh gas add valve. John R. Clarke figure.

With a 50-W workload set on a bicycle ergometer, $\%FIO_2$ decreased steadily in all divers. The rate declined faster with a 75-W workload than a 50-W workload. If we had not been monitoring the divers, they might have lost consciousness from hypoxia within a few more minutes.

In similar tests of the Dräger Extreme CMI rebreather (Figure 13), the NEDU found that the "tightening down" of an exhaust "pepper" valve caused $\%FIO_2$ to drop. We later discovered that such action would inflate the breathing bag, making it more difficult for the demand add valve to function when workload is high. The dependable functioning of the demand value is a safety feature to enrich the breathed gas when metabolic demand exceeds the oxygen available in the fixed fresh gas flow rate.

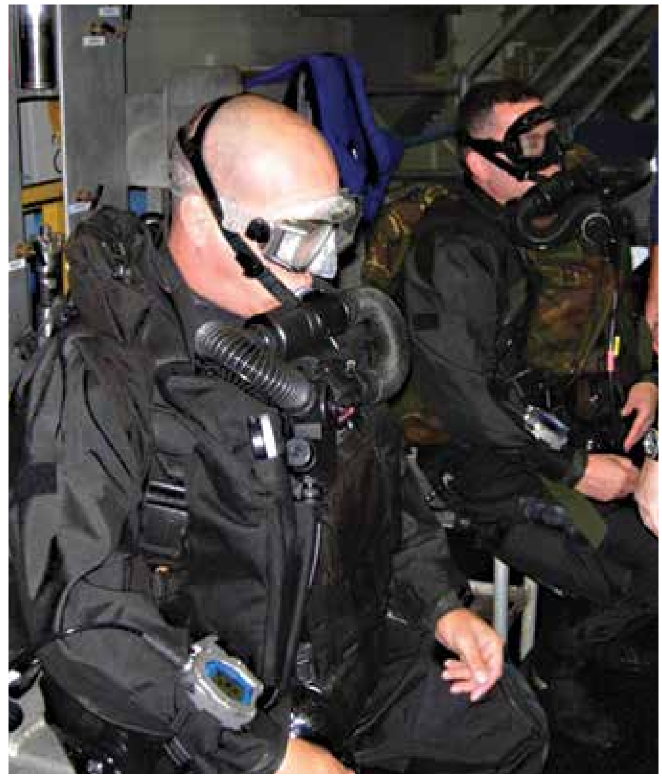

Figure 14. Divex Shadow Excursion diver instrumented with an oxygen sensor and data recorder. Photo by John R. Clarke.

Out of concern for the new, smaller form-factor semiclosed-circuit rebreathers, such as the Viper SC and the Divex Shadow Excursion, we insisted that there be an oxygen monitor attached. For instance, in our testing of the Shadow Excursion we linked a Dräger oxygen monitor, installed in a special block in the inhalation hose, with a VR3 computer to log and display PO_2 in a downloadable format.

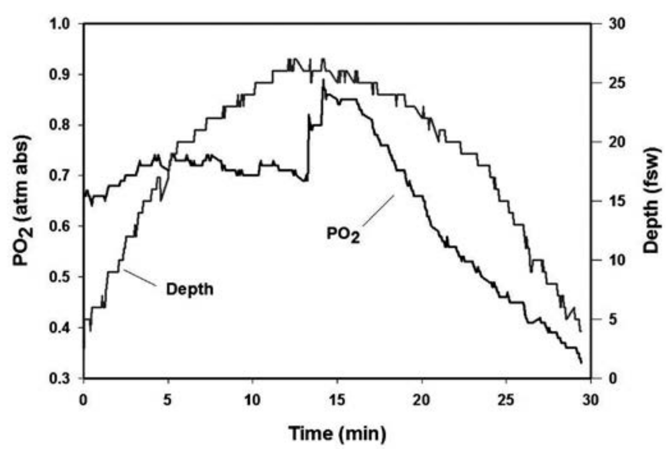

Figure 15. PO_2 and depth profile for an instrumented diver making a beach dive. John R. Clarke figure.

The combination of constant mass injection rebreathers and an oxygen monitor was exploited by Clarke (1999a) and Smith (2008) to estimate oxygen consumption during operational dives. Smith showed that the driving of a large diver propulsion device is not always as restful as anticipated. In a few divers oxygen consumption was relatively high, leading to surprisingly low bag oxygen concentration, just as was observed in Figures 12 and 13.

Figure 15 shows the plots obtained from an instrumented diver swimming a bottom-hugging profile away from a beach. The diver paused at 26 ft (8 m) and then returned to the beach. The gray line is the depth profile, and the black line is the PO_2 tracing. The PO_2 varied around 0.7 ATA until the diver paused at the end of the outward transit. During that pause the inspired PO_2 rose to a peak of about 0.9 ATA before the diver started his return to the beach. During the return the combination of a vigorous swim and increasingly shallow depth caused a rapid decline in inspired PO_2. Fortunately, the diver reached the beach before reaching dangerously low PO_2 levels.

MODELING OF CMI REBREATHERS

The surprises NEDU received during testing of the new generation of constant mass injection rebreathers led us to begin modeling those rebreathers. Although we had already solved the differential equations describing the time course of changes in inspired oxygen partial pressures, we needed a realistic, interactive model that took into account complex dive profiles, the effect of manual addition of fresh gas, and the effect of exhaust valve setting on breathing bag volume. A fully inflated breathing bag resulting from a tightly adjusted

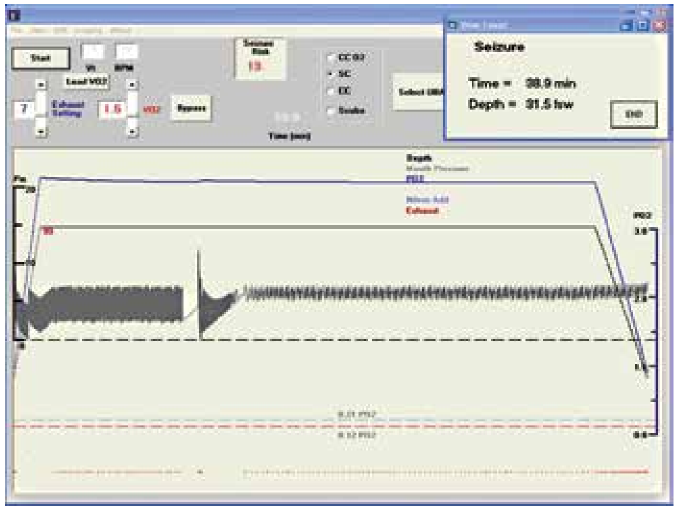

Figure 17. Simulated dive resulting in an oxygen seizure. John R. Clarke figure.

exhaust valve made it difficult for manual add valves to operate when divers were working hard. As seen in the NEDU test pool (Figure 13), hypoxia therefore became likely.

The NEDU software Semiclosed, first revealed at Rebreather Forum 2.0, allowed us to see in an interactive manner the complex effects of real dive actions — namely, changes in

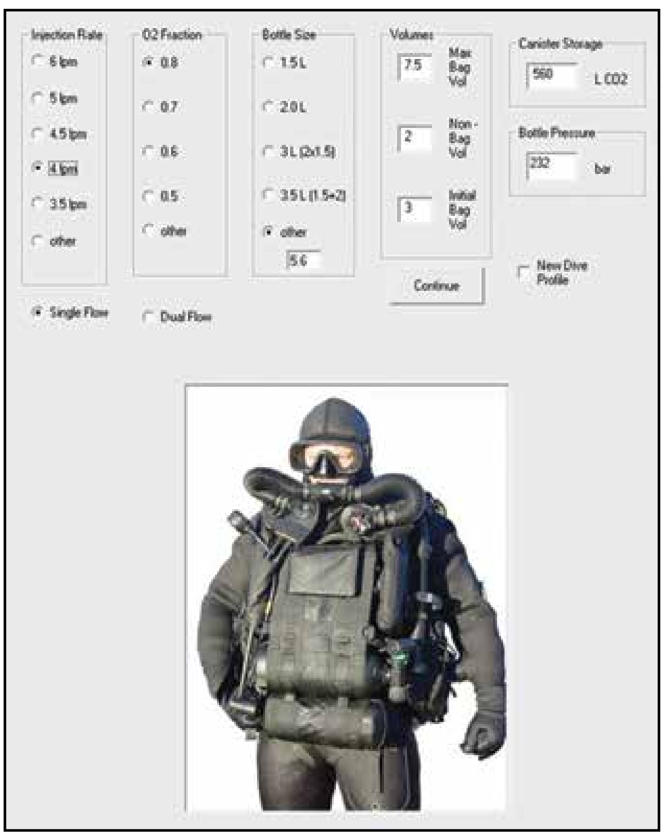

Figure 16. Semiclosed-UBA definition screen. John R. Clarke figure.

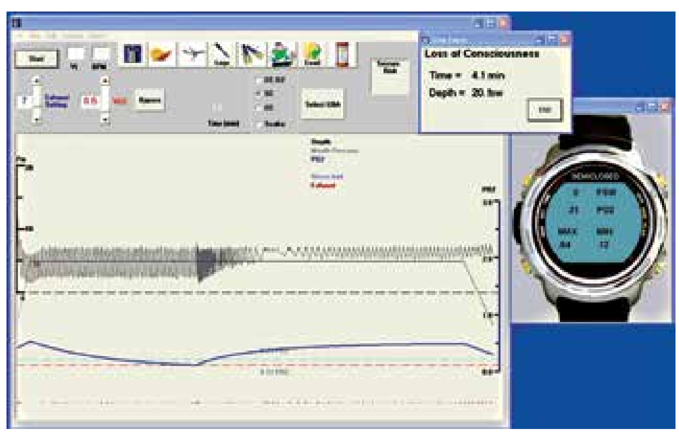

Figure 18. Simulated dive resulting in loss of consciousness due to hypoxia. John R. Clarke figure.

depth, changes in exercise (oxygen consumption), manual gas addition and exhaust valve adjustments.

The setup screen (Figure 16) allows the definition of the UBA's fresh gas flow rate, oxygen fraction, gas bottle floodable volume, breathing bag and total gas volumes, CO_2 scrubber canister capacity, and starting bottle pressure. After the simulated dive has begun, dive results are shown (Figures 17 and 18 are examples.) The main display window shows the diver's depth, inspired PO_2, and respiratory pressures, both dynamic with breathing and static, as affected by counterlung static pressure. Physiological events are shown, including loss of consciousness from too low a PO_2 (Figure 18), and a more random event: seizure from too high a PO_2 (Figure 19).

The dives do not end after the physiological event because the model assumes the diver is wearing a full-face mask. The events become self-limiting as long as the diver does not drown — the great advantage of a full-face mask.

TIME COURSE OF PO_2 CHANGES IN CMI REBREATHERS

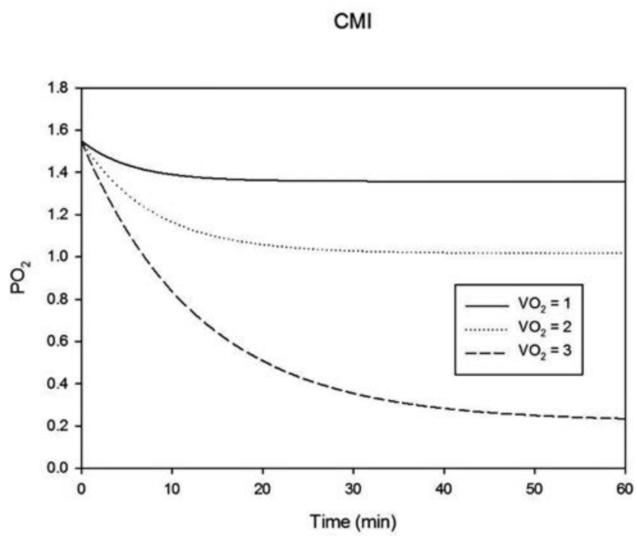

Figure 19. Variation in inspired PO_2 by calculation from Nuckols et al. (1999). John R. Clarke figure.

Nuckols et al. (1999) expanded upon Clarke's equations and mathematically modeled the time course of inspired PO_2 changes in a CMI rebreather at 40 fsw (12 msw), with a 4.5 L·min^{-1} fresh gas injection of nitrox with 70 percent oxygen. Figure 19 plots the changes expected for work rates (oxygen consumption) increasing from 1 to 3 ATA per minute. For comparison, this PO_2 versus time tracing (Figure 19) will be seen to vary below with other types of semiclosed-circuit rebreathers.

CONSTANT VOLUME INJECTION

The original AGA ACSC, or its current version DCSC (Figure 20), is a constant volume injection (CVI) semiclosed-circuit rebreather. It controls inspired oxygen far better than the CMI rebreather because fresh gas addition is linked to diver ventilation through a rotating cam (Figure 21). As the diver works

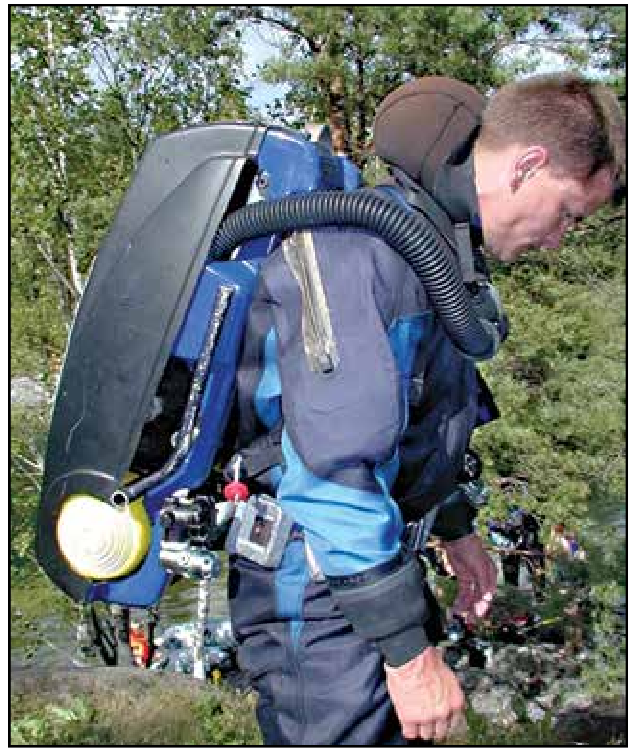

Figure 20. Interspiro DCSC. Photo by John R. Clarke.

harder, he breathes harder. The more rapidly he breathes, the more gas is injected into the breathing loop. Typically, fresh gas is injected on every fourth breath.

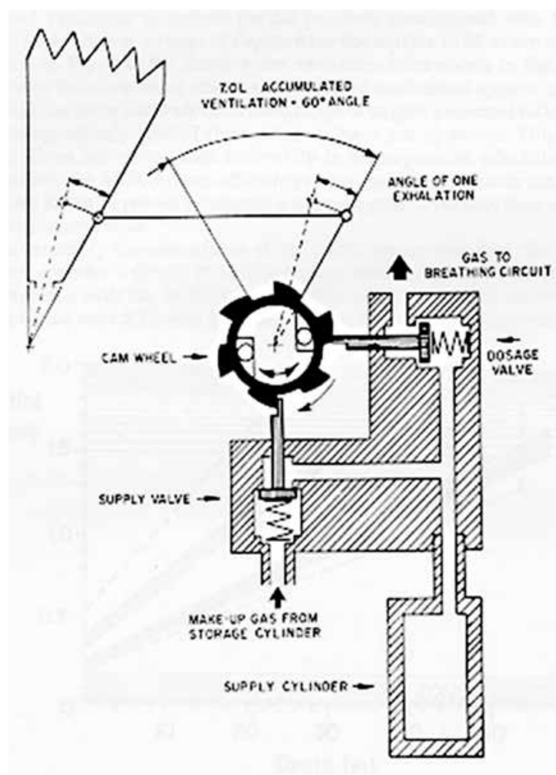

Figure 21. Interspiro ACSC ventilation control mechanism.

The equations governing oxygen partial pressure in a CVI unit are found in Nuckols et al. (1999). In the application of those equations to a dive to 40 fsw (12 msw) and oxygen consumption rates (work rates) of 1.0, 2.0 and 3.0 $L \cdot min^{-1}$, the stabilized oxygen partial pressure varied only from 1.3 to 1.4 ATA (Figure 22). For 1.0, 2.0 and 3.0 $L \cdot min^{-1}$ oxygen consumption, breathing frequency was assumed to be 20, 30 and 40 breaths per minute, respectively.

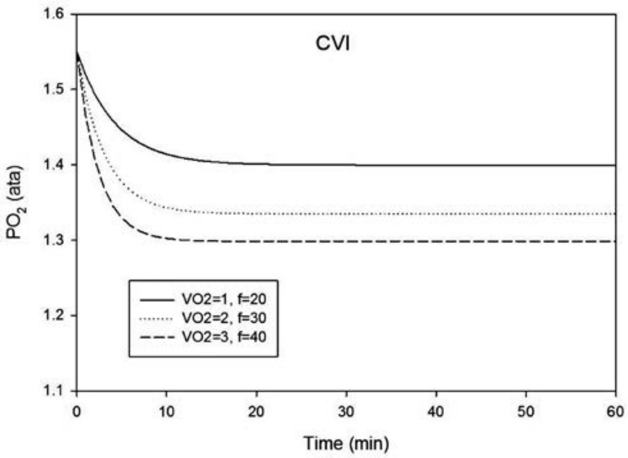

Figure 22. CVI rebreather PO_2 control for three levels of oxygen consumption and three respiratory frequencies (breaths per minute). John R. Clarke figure.

Figure 23. Halcyon RB80.

Figure 24. Aqualung Oxymix 3C. Photo by John R. Clarke.

In Figure 22, derived from Nuckols et al. (1999), we assume the following: The diver's depth is 40 fsw (12 msw), his fresh gas mixture contains 70 percent oxygen, each gas injection contains 0.1 L of gas, injection bottle pressure is 135 psi over ambient, and total system gas volume (UBA and diver) is 9.0 L. Every fourth breath triggers a fresh gas injection.

In this modeled dive, inspired oxygen partial pressure stabilized to within the range of 1.3 to 1.4 ATA, depending on oxygen consumption (work rate) and breathing frequency in $breaths \cdot min^{-1}$. This PO_2 range is a marked improvement over the PO_2 variation found in the CMI rebreather. However, that improvement comes at the cost of size, weight and complexity. The Interspiro DCSC weighs about 75 lb (33 kg).

VARIABLE VOLUME EXHAUST (VVE)

The Halcyon RB80 and the Aqualung Oxymix 3C are two semiclosed-circuit rebreathers that elaborate upon the ventilation controlled concept of the DCSC by exhausting gas proportionately to the volume of gas moved with each breath. Rather than being a function of respiratory frequency, it is a function of minute ventilation, or respiratory minute volume.

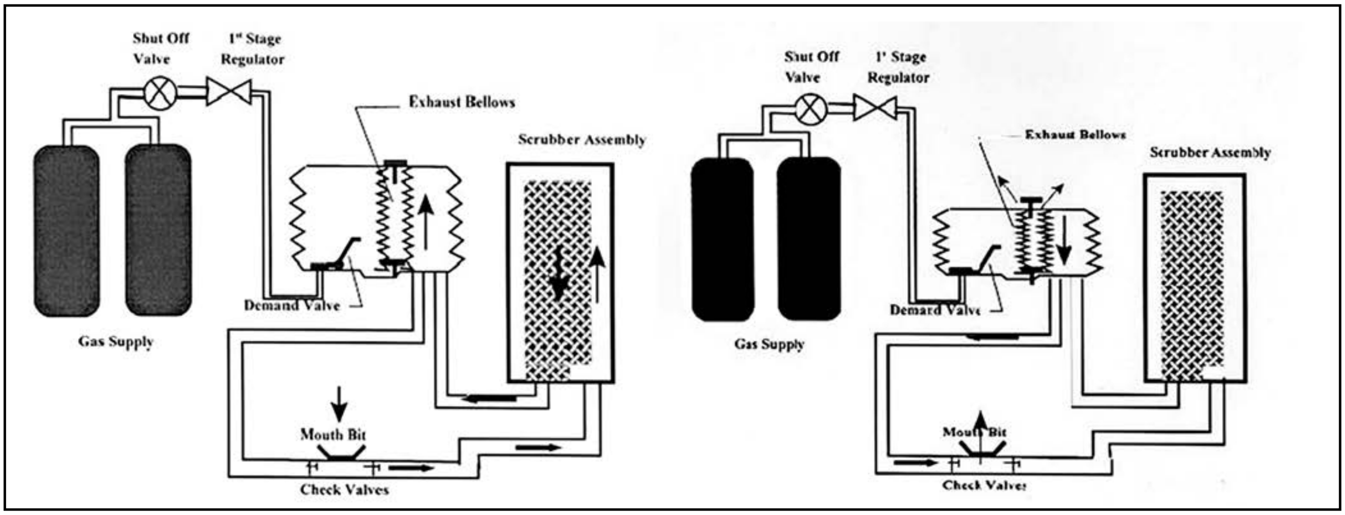

Figure 25. Schematics of the bellows-in-bellows action of dual-bellows VVE rebreathers. The exhalation phase is shown in the left panel, and inhalation is shown in the right panel.

A VVE rebreather benefits a diver who breathes slowly but deeply, compared to a shallow- and fast-breathing diver.

The current RB80 weighs about 20-30 lbs (9-14 kg) without gas bottles, and the self-contained Oxymix 3C weighs about 49 lbs (22 kg) with all consumables on board.

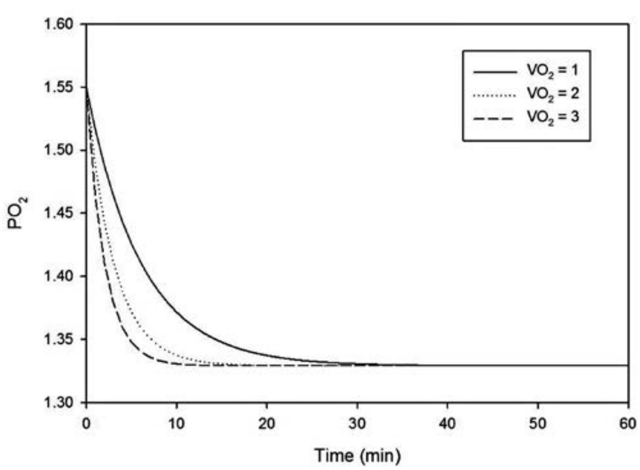

Figure 26. VVE rebreather PO_2 control for three levels of oxygen consumption and three RMVs. John R. Clarke figure.

The modeled parameters, taken largely from Nuckols et al. (1999) result in precise PO_2 control once PO_2 has stabilized. Results of a dive to 40 fsw (12 msw) are shown for three oxygen consumption rates: 1.0, 2.0, and 3.0 L·min^{-1}. Corresponding respiratory minute volume (RMV) varies from 25, 50, to 75 L·min^{-1}, respectively.

Figure 27. Oxymix 3C inner (exhaust) and outer bellows (left and right panel). The demand valve actuator is pointed out in the right panel. U.S. Navy photo.

As pointed out by Franberg (2011), the Nuckols PO_2 control equations assume a fixed ratio of ventilation to oxygen consumption, an assumption that is probably not valid across time or divers. In other words, your results may vary.

Arguably the simplest VVE semiclosed-circuit rebreather is the KISS GEM (Figure 29), which affects its ventilation-proportioned exhaust by keying to diver ventilation through a unique mechanism in the mouthpiece that exhausts the first part of CO_2-rich exhalation (US Patent 20130186402).

SEMICLOSED-CIRCUIT REBREATHERS IN SATURATION DIVING

When conducting saturation dives using helmets and umbilicals supplied from a diving bell, divers carry a scuba cylinder on their back as an open-circuit bailout in case of loss of gas from the umbilical. At saturation diving depths down to 1,000 fsw (305 msw), that bailout gas would last no more than five minutes, which leaves the diver very little time to return to the safety of the diving bell.

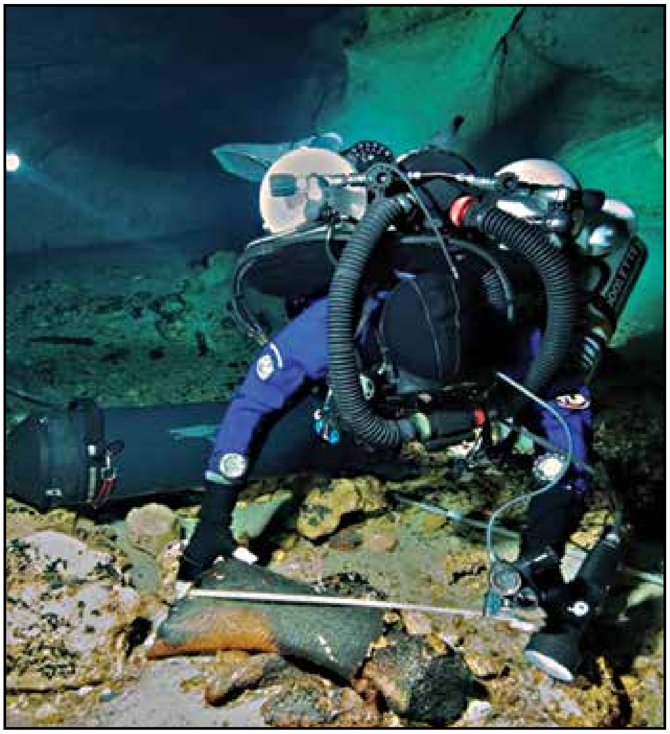

Figure 28. The Halcyon RB80 and David Doolette at 300 ft (91 m) in their natural environment. Photo by David Rhea/WKPP, 2011.

Figure 30. A saturation diver working on the turret support structure during the turret recovery from the USS Monitor. Photo by Eric Lippmann.

Figure 31. The DIVEX saturation diving system under test at NEDU. U.S. Navy photo.

Figure 29. The KISS GEM semiclosed-circuit rebreather incorporating a standard aluminum 80 cu ft cylinder. Photo by Mike Young.

NEDU divers have tested the Divex Gasmizer saturation diving system down to 1,000 fsw (305 msw). Key among the Divex innovations is a semiclosed bailout called the Secondary Life Support System (SLS) backpack. By having the bailout unit be semiclosed, gas duration is enhanced, allowing the diver increased opportunity to return to safety.

The backpack is a complete semiclosed-circuit rebreather using CMI. Over-the-shoulder breathing bags are

Figure 32. The Divex SLS MK IV semiclosed-circuit rebreather emergency backpack. Photo by David Dekker.

released from the shoulder straps when a parachute-type lanyard is pulled by the diver. The SLS backpack provided about 22 minutes of breathing gas at 1,000 fsw (305 msw) (Swiergosz and Steckel, 2005), more than enough time for a diver to return to the safety of his diving bell.

CONCLUSIONS

Semiclosed-circuit rebreathers fill a multitude of diving roles from shallow-water recreational diving to deep cave diving and very deep saturation diving. They are preferred over electronic rebreathers in many applications due to their robust mechanical nature and dependability.

The large and bulky military semiclosed-circuit rebreathers of the 1950s and ’60s have been replaced by smaller and lighter units, reflecting changes in the diver population. However, those design changes have made CMI rebreathers more susceptible to hypoxia than the older high-flow designs due to high diver workload at shallow depths. Whereas CMI rebreathers are about as simple as a rebreather can be, their safe use is not guaranteed without careful diver education. NEDU’s Semiclosed software is a useful educational tool for training on CMI rebreathers. With low flow-rate CMI rebreathers, an oxygen monitor is highly advisable.

The U.S. Navy’s semiclosed-UBA inventory only uses CMI devices (Carleton Viper SC and Divex SLS MK IV backpack). CVI and VVE rebreathers have overcome some of the operational vulnerabilities of the CMI rebreathers but at a cost in size and complexity. Nevertheless, the fact that some VVE devices are used for critical and deep underwater cave exploration is a testament to the value of the entire class of semiclosed-circuit rebreathers.

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KMS Prinz Eugen, *Kwajalein Atoll, Marshall Islands. Photo by Andrew Fock.*

OPEN-CIRCUIT DIVER FATALITIES

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INTRODUCTION

Divers Alert Network (DAN) has been collecting data on diving injuries and fatalities since 1987. Each year the DAN Research Department receives information from a variety of sources on an estimated 1,000 cases of decompression illness (DCI); in 2006, DAN received notification of 138 scuba diving fatalities (Pollock et al., 2008). Annually, there are an unknown number of non-DCI injuries and other non-injury incidents occurring that, until recently, were not reported to DAN. This incident information can now be reported through accessing DAN's online diving incident reporting system. Incidents, even those not resulting in injury, are very important in identifying issues that could compromise diver safety. In the analysis of industrial accidents, the ratio of reported incidents to a fatality is 600:1 (Bird et al., 1996). Therefore, reducing the number of incidents could have a positive effect in reducing the number of diver fatalities. DAN DCI data has been published annually in what has been known as DAN's *Annual Diving Report*.

Over the past few years, DAN has made a concerted effort to quantify the incidence of decompression sickness (DCS) in all types of diving. This process has been difficult, if not impossible, in the past due to a significant lack of baseline data about the number of safe dives made. Without this denominator, it is impossible to come up with an accurate incidence of injury for the types of diving done by recreational divers. To address this serious safety issue, DAN researchers collected data on the number of dives made by divers while diving in four different circumstances (liveaboards, shore/day-charters/personal watercraft, diving professionals and cold/deep/wreck diving). DAN researchers downloaded diving data from dive computers in each of these situations and determined that the incidence of DCS ranged from 1.0-29.20/10,000 open-water dives (Table 1: Incidence of injury in recreational scuba diving) as compared with a diver fatality rate of 15-20/100,000 divers (Sleet et al., 2014).

Table 1. Incidence of injury in recreational scuba diving.

Group	# Dives	Incidence of DCS*
Liveaboard	19,909	1.0
Shore/Charter	16,356	3.2
Dive Professional	5,090	10.0
Coldwater/Deep	5,139	29.2

*- DCS cases per 10,000 dives

DIVING FATALITY DATA

A review of DAN historical diving fatality data has demonstrated that there are trends that need to be addressed. With the aging recreational diving population in the U.S. (the average age of injured recreational divers being somewhere between 40 and 50), diseases associated with age are likely to be an issue. When reviewing sports-related deaths, coronary artery disease is the leading cause of sudden cardiac death in those over the age of 35. The risk of cardiac-related death in recreational divers steadily increases with age with those over the age of 50 having a risk 10 times greater than divers under the age of 50 (Denoble, 2013).

While scuba diving in all its various forms is inherently safe, it is not without risk. When scuba diving, the underwater environment alone can give rise to a significant number of potential risks. From the latest DAN diving accident and fatality data, the majority of deaths while diving are simply listed as drowning. While drowning may very well be the ultimate outcome of a diving accident, there may be any number of factors leading up to this final, fatal result. DAN data have indicated that approximately 28 percent of diving fatalities each year are a result of cardiac events during the dive. While these divers may very well have had a similar cardiac event take place while jogging, gardening or even sleeping, they occurred during a diving excursion and, therefore, are classified as a diving fatality. Although it is disturbing that these fatalities occurred while participating in an otherwise safe and enjoyable sport, it is most distressing is that approximately 60 percent of those who died as a result of a cardiac event associated with scuba diving had signs and/or symptoms that were recognized as cardiac-related before or during the dive, but they continued to dive anyway. Had they or one of their diving companions recognized the signs or symptoms as cardiac-related, they could have simply "called" the dive or questioned whether it was prudent to continue, and the fatal situation may have been averted.

Apart from cardiac issues, DAN data reveal that limited experience may also be a serious and significant issue in diving fatalities. Entry-level divers appear to be at greatest risk (Figure 1).

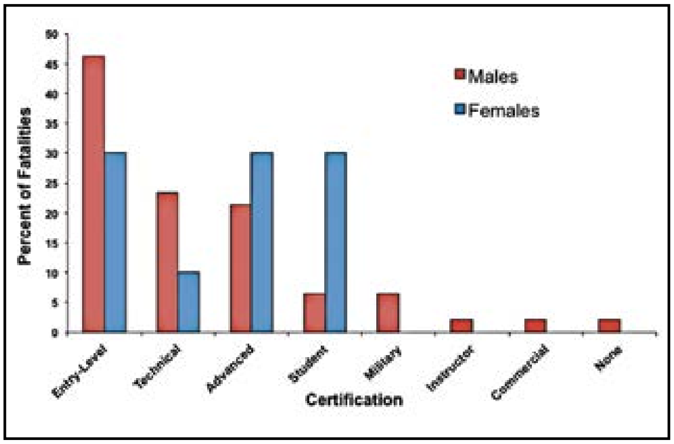

Figure 1. Certification of diver fatalities (Vann et al., 2006)

DAN data also show that those certified for one year or less who may have limited experience to draw from in an emergency may be at the greatest risk (Figure 2). The number of years a diver has been certified may not, in reality, be an accurate indication of his ability to manage risks in diving. For example, a diver may have taken a certification course 10 years ago but not made a sufficient number of dives to maintain critical skill proficiency.

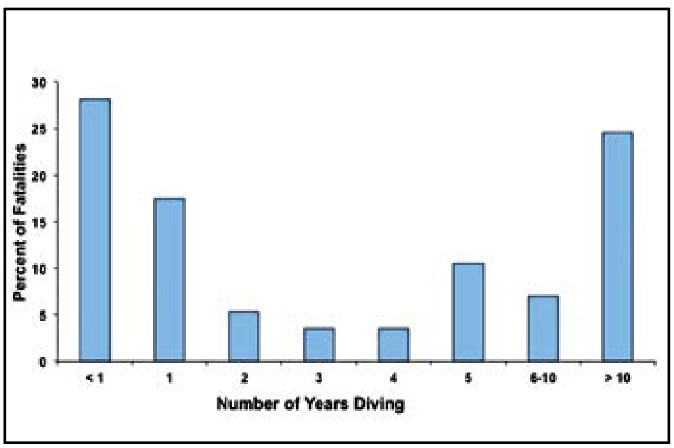

Figure 2. Number of years since initial certification (Vann et al., 2006)

DAN data (Figure 3) demonstrate that divers with fewer than 20 dives in the 12 months prior to a fatal diving accident were at the greatest risk. This table also shows a significant number of fatalities with the group of divers who had made more than 300 open-water dives in the previous 12 months (Vann et al., 2006). This could indicate that divers who dive regularly may have a cavalier attitude toward their own safety, thinking that their proficiency in the water will allow them to manage any emergency.

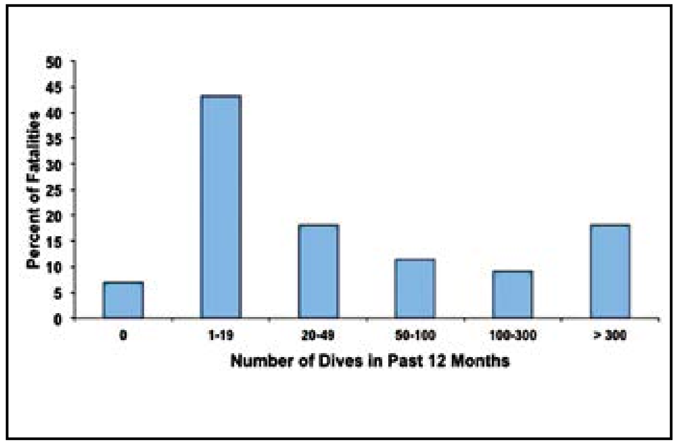

Figure 3. Number of dives in 12 months prior to accident (Vann et al., 2006)

DAN fatality data may also indicate that body mass index (BMI) may be a factor increasing the likelihood that a diving emergency will turn into a fatality (Figure 4). BMI was determined as part of the data collected by DAN researchers in three different data sets: Project Dive Exploration (PDE), the DAN Injury Database and the DAN Fatality Database. The BMI indicated in both the PDE and DAN Injury Database may be reflective of the average BMI found in the greater recreational-diving population, while the BMI in the DAN Fatality Database appears to be skewed toward the overweight and obese categories. While BMI may not necessarily predispose a diver to injury or fatality,

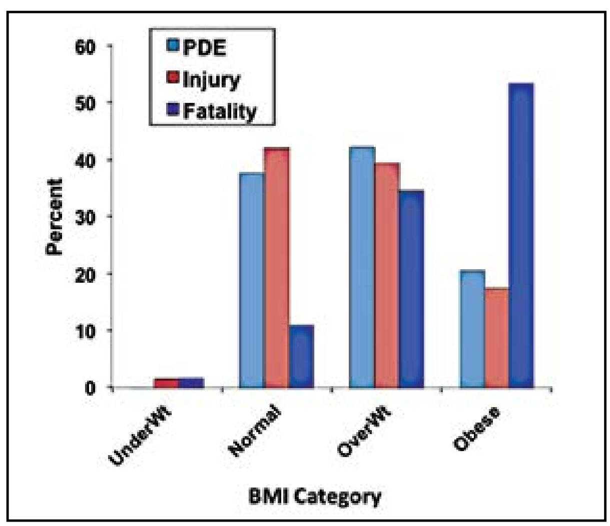

Figure 4. Body mass index in the diving population (DAN data)

it may indicate a lack of exercise tolerance or other underlying medical condition that may reduce the diver's ability to successfully manage a diving incident or emergency.

Recently, DAN researchers reviewed the accumulated fatality data and conducted a root-cause analysis of 947 recreational diving fatalities between 1992 and 2003 from the DAN Fatality Database to determine what circumstances and events lead to diver deaths (Denoble et al., 2008). In this analysis, DAN researchers identified four different phases in the cascade of events leading to a fatality: the trigger, the disabling agent, the disabling injury and the cause of death. As the earliest identifiable root causes that transform dives into emergencies, the triggers merit special attention. Identifying these triggers (Table 2) is essential so that divers can avoid or manage them during dives.

Table 2. Triggering events in a diving fatality.

Running out of breathing gas	**41%**
Entrapment	**21%**
Equipment problems	**15%**
Rough water	**10%**
Trauma	**6%**
Buoyancy	**4%**
Inappropriate gas	**3%**

The data indicate that the most significant trigger was running out of breathing gas underwater. To put this in context, nearly 400 divers from the cases studied might have survived the dive had they managed their gas supply correctly. Because of the equipment standard in diving today, running out of breathing gas underwater, especially before any other problems occur, simply should never happen.

Be "air aware." Always begin dives with a full cylinder of breathing gas and end dives (standing on the boat, dock or shore) with gas remaining. Before initiating a dive, all divers should decide how to communicate information about their remaining gas supplies during the dive. They should also establish and communicate to each other the point at which to begin making their way to the exit. That may be when the first diver reaches half of his breathing-gas supply, but it may be sooner than that.

Many cave divers use the rule of thirds, which has divers using the first third of their gas supply for the dive, the second third for the exit from the cave or the ascent, and the final third set aside for contingencies. This may seem conservative for open-water diving, but the idea of leaving a significant reserve for emergencies or other unexpected circumstances is absolutely relevant. Anything short of total management of the breathing gas puts divers, their buddies and every diver in the vicinity at risk.

The next most common trigger in dive fatalities (21 percent) is entrapment. Nearly 200 divers in this research found themselves trapped in an overhead environment and were unable to get back to open water. An overhead environment, such as a cave, cavern, and submerged wreck or under an ice sheet, is any diving situation in which a diver does not have direct, vertical access to the surface. Every training organization warns divers about the dangers of entering such environments without appropriate training, experience, planning and equipment. The way to mitigate the hazard of this trigger is very simple: Never enter overhead environments without being truly prepared, trained and qualified to do so. When in doubt, stay out.

The third most common trigger identified in the fatality analysis was equipment problems. This trigger caused 15 percent, or about 150, of the fatalities studied. Notably, this does not mean the equipment failed or that its design was flawed. Rather, the problems were most often a result of user error. These errors included improper use, failure to ensure correct configuration, lack of maintenance and insufficient familiarity with the equipment. Dr. George Harpur, an experienced investigator of dive fatalities in Ontario, states, "We are not able to document a single case in which equipment malfunction directly caused a diver's death or injury. It has been the diver's response to the problem that results in the pathology." It is important to remember that dive equipment is life-support equipment. Learn about all its features and functions, practice with it, and maintain it; take care of each piece of equipment so it will function properly in all situations.

Knowing how divers get into serious trouble only advances the discussion so far. For diving to be safer, we must apply the lessons that can be taken from these tragic events. How can we, as divers, reduce the likelihood that these triggers will cause problems for us?

The identified triggering events initiated a cascade that, unless positive corrective actions are taken, can result in injury or death. I have called this series of events the "Cascade toward death" (Figure 5).

Figure 5. Cascade toward death.

The next step in this cascade of events is "harmful action," which, by definition, is a root cause (generally a reaction rather than a practiced action) that exacerbates the situation. The most common harmful action is an emergency ascent (55 percent). This indicates that when confronted with an emergency situation, the majority of divers chose emergency ascent or attempted to escape to the surface rather than manage the situation underwater. If no positive corrective action is taken and the cascade continues, the next phase is identified as "incapacitating injury." By definition, incapacitating injury is an action that caused death or rendered an incapacitated diver susceptible to drowning. The research data show that asphyxia was identified as the most common injury in this cascade. As the cascade continues, the final phase is the cause of death specified by the medical examiner and might be the same as the incapacitating injury. The most frequent cause of death is drowning.

REDUCING THE RISK

Understanding the series of events that can take place once an emergency is triggered thus turning a relatively unremarkable and enjoyable recreational diving experience into a tragedy is critical in developing ways for divers to reduce the likelihood of an emergency and mitigate risks.

Education

Take full advantage of every opportunity to learn. Read dive magazines, spend time with experienced divers, attend dive club meetings, and check out dive-safety lectures or seminars online. More knowledgeable divers are safer divers. Divers should be thoroughly trained in the type of diving they intend to do, but they should not stop learning when they leave the classroom — treat every dive as an educational experience. Use any unexpected incidents that occur while diving as opportunities to brainstorm and discuss response options, contingencies and prevention strategies with dive buddies.

Practice

Dive skills and emergency-management skills require constant practice and reinforcement. All divers should refresh their basic diving and emergency skills often, especially when they have not been diving in a while. Being thoroughly familiar with the use of any new equipment by practicing with it in a controlled environment is recommended before using it in open water. Although practice may not make every diver perfect, it will help divers make the correct decisions and manage problems appropriately rather than trying to escape to the surface.

Experience

The value of experience cannot be overstated. Divers with limited experience, including those returning to the sport after a long absence, are at greatest risk. Divers should consider that the number of dives in their logbook or the date on their certification card (C-card) does not automatically qualify them for greater challenges in the sport. Certification is not the same thing as proficiency. Divers who have been away from the sport for some time should take a refresher course or do their first dive under supervision of a certified instructor or in very controlled and benign conditions. According to DAN fatality data, 88 percent of the divers died on the first dive of their planned dive series. Safety-conscious divers expand their diving horizons gradually, making sure they do not outpace their training and level of comfort. To truly be prepared for more advanced diving, slowly and methodically increase the complexity and task loading of dives. Remember, divers are advised not to dive their C-card but to dive their experience.

Health

As previously mentioned, approximately one-third of the fatalities studied involved cardiac problems. Amazingly, in the majority of these situations the divers who ultimately died had symptoms such as shortness of breath, chest pain or fatigue but proceeded to dive anyway. Most divers are aware of the importance of good general health and fitness for diving, but comfort and well-being at the time of the dive are also important. If not feeling up to a dive, do not dive.

The majority of these cardiac cases were associated with a pre-existing condition. Cardiac events are not restricted to the much older diving population or to the male gender. It is suggested that all divers over the age of 35 have an annual physical. A physical is also recommended following any noticeable change in an individual's health status. Divers might benefit from having their physical exam performed by a physician trained in diving medicine. If divers do not know a physician in their area who is familiar with diving medicine, call the DAN Medical Information Line (+1-919-684-2948). DAN has more than 700 physicians in its physician referral database.

Predive preparation

As divers prepare to dive, it is a good idea to configure and assemble all diving equipment as a buddy team so that anything that looks odd or out of place can be identified and corrected. This also provides an opportunity to familiarize each diver with the other diver's equipment. If boat diving, it may be helpful to assemble and configure all diving equipment before the boat leaves the dock. This is especially true for those subject to seasickness, since it minimizes the amount of time spent on the rocking boat deck conducting preparatory tasks. Hastily assembling diving equipment in rolling seas while feeling nauseated can increase the likelihood of potentially hazardous errors.

Before diving, all divers should review their dive plan with their buddy to ensure a shared understanding of the goals for the dive. It is essential to agree on the route to be taken and possible alternatives to the primary dive plan. It is much easier to communicate the switch to plan B if a plan B was decided and agreed upon before the dive begins. Establish the fact that anyone can terminate a dive at any time for any reason, even before the dive begins, without repercussions. Creating an environment in which divers feel comfortable making such calls builds a culture of diving safety.

Develop and continually reinforce a predive ritual. It should involve equipment checks, dive plan review, hand signal review, diver separation protocol review and out-of-breathing-gas procedure review. This may seem unnecessary if the same people dive together regularly, but these rituals are time well spent if they reduce the likelihood that anyone will be unprepared to dive. The use of a checklist to assist in this ritual is highly recommended. Never say, "Do not worry, I will take care of you." That means one of the divers is not as qualified or prepared for the dive as he should be — a formula for disaster. Anyone making a dive should do so only if he is fully prepared and wants to dive, not because someone else wants him to.

The dive

Once in the water, each diver should check the other to make sure all equipment is secure and in place, there are no leaks and that buoyancy is properly calibrated. Give and receive the OK sign, initiate the preparatory ear-clearing procedures, and begin a controlled descent. Descending feet first using a fixed line makes it easy to stop the descent should the need arise and may be advisable if a current is present. If there is any doubt during the initial phase of the descent or preparation for the dive, make a short stop 15-20 ft (5-6 m) below the surface to give and receive the OK sign before proceeding to the bottom. Maintain constant awareness of circumstances during dives, and know when to call off a dive. Situational awareness is a critical component of diving safety as it allows the diver to accommodate for circumstances that could compromise safety. It is always wise to plan the dive and dive the plan, but be prepared to modify a dive plan if conditions call for a more conservative approach. Working harder during the dive than anticipated, for example, can increase air consumption and increase inert gas absorption at depth, so divers should watch their air consumption more closely and possibly limit the time spent at depth.

As divers move underwater, their pace should be dictated by the slowest diver in the group. Divers should never assume that another diver can keep up with them. If diving in a group of three or more and one diver decides to abort the dive for whatever reason, either terminate the dive as a group or escort the diver back to the exit point, making sure he is safely out of the water before continuing the dive.

CONCLUSION

Does this examination of diving fatalities indicate that recreational diving is inherently dangerous? No. There are millions of certified divers who have made tens of millions of safe, enjoyable dives without incident. But consider that there is risk in every outdoor activity. Is this risk discussed in this paper unreasonable? That is for each individual diver to determine. A degree of risk will always be part of scuba diving, but it is a risk that can be identified and managed.

Scuba diving is a fantastic sport enjoyed by young and old alike. The focus should always be to maximize enjoyment while minimizing risk. Challenges are overcome in and under the water by thorough preparation, physical capability and the effective application of knowledge and skill.

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HMS Hermes, *Sri Lanka. Photo by Andrew Fock.*

RECREATIONAL SCUBA DIVING FATALITIES BY THE NUMBERS

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INTRODUCTION

Underwater diving occurs in an unnatural environment for human species and is perceived by the general public as dangerous. Indeed, the subaquatic environment entails hazards associated with lack of breathable gas, forces related to pressure, gas physics, water movements, dangerous marine life and others. With special diving equipment that provides a continuous supply of breathing gas, protects from adverse environmental effects and improves control of vertical and horizontal mobility, divers may stay underwater longer and venture deeper than they could on a single breath. However, for diving to be reasonably safe, divers must be fit and trained, equipment must be adequate and reliable, human-machine interaction must be seemingly flawless, and divers have to adhere to safe diving practices that help to control hazards. In case complex human-machine system fails, environmental forces exceed human tolerance, or an intrinsic acute health problem occurs, divers face life-threatening situations and sometimes die. Regardless how seldom this happens, an untimely death of a person always brings up the question if diving is too dangerous.

Indeed, injuries and fatalities in recreational diving cause significant losses and affect the adversely injured, their families and the entire diving industry. In the context of total injury burden, diving fatalities comprise only 0.013 percent of all causes of injury mortality in populations over 15 million in Australia (Buzzacott, 2012) and 0.045 percent in the U.S. (based on 150,000 injury deaths reported by the Centers for Disease Control and Prevention (CDC) for 1999 (Anderson and Smith, 2005)). Thus, diving fatalities represent a minor public health problem, but for the recreational diving community in the U.S. and Canada it is 80 to 90 deaths every year (Vann et al., 2004a) that could have been avoided. Despite genuine interest of the diving community for prevention of diving injuries (Vann and Lang, 2010), the efforts fall short of the current public health model of injury control and prevention (Fleming and Binder, 2002).

Modern epidemiology offers a set of tools for studying associations of exposures to health outcomes, discovering of causal relationships, designing and evaluating preventive interventions and monitoring their impact (Heinrich, 1941a), but they are not commonly used in dealing with diving injuries and fatalities. Most efforts in diving communities are limited to collection of injury data, while the evidence-based preventive interventions are missing. Injury control and prevention are possible only if the entire community is involved (Bonnie et al., 1999). To enhance that, the common language in public discourse about diving injuries has to be advanced and epidemiology methods introduced. The purpose of this article is to highlight basic terminology necessary in that process.

HAZARDS, RISK AND EXPOSURE

By definition of the Federal Aviation Administration (FAA), hazard is a “condition, event, or circumstance that could lead to or contribute to an unplanned or undesirable event” (FAA, 1998). Another definition describes hazard as any biological, chemical, mechanical, environmental or physical agent that is reasonably likely to cause harm or damage to humans, other organisms, or the environment in the absence of its control (Sperber, 2001). Humans may also be a source of hazard by engaging in unsafe behaviors and acts or by failing to perform standard procedures designed to control hazards and mitigate risk (human error, operator error) (Edmonds and Walker, 1989; Liberatore, 1998; Reason, 2000; Acott, 2005).

Table 1. Selected list of hazards in diving, their sources and injuries they may cause.

Source	Hazard	Injuries
SCUBA	Loss of gas supply	Asphyxia, drowning, death
Increased gas density	Hypoventilation	CO2, intoxication, loss of consciousness, drowning
Aquatic environment	Loss of buoyancy control	Sinking (drowning), uncontrolled ascent
Environmental pressure	Rapid decompression	DCS, AGE
Dangerous marine life	Shark attack	Bites, bleeding
Wreck diving	Entrapment	Drowning
Rebreather diving	Oxygen sensor failure	Hypoxia, oxygen toxicity, drowning

Hazards in diving are many, and some are shown in Table 1. Some underwater diving hazards stem from the circumstance that diving occurs in an unbreathable environment and are present continuously throughout the dive. Underwater breathing equipment is another source of continuously present hazards. Other hazards may arise due to diver’s unsafe behavior or acts, changes in environment or acute health changes (HSE, 2001; Fisher et al., 2009). While hazards associated with diving cannot be eliminated, they can be controlled if they are identified. Control measures for known hazards reduce the likelihood that it will cause injuries or that the injuries will be severe. Standard diving procedures are intended to include control measures, but there are no generally accepted definitions of good diving practices in recreational diving.

Hazard identification is a qualitative analytical process and a first step in hazard analysis and risk assessment. It may be established intuitively or by various formal methods such as Failure Mode, Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA). FMECA is an inductive, bottom-up analytical procedure providing a qualitative analysis of possible bad outcomes in case of failure of basic components of the system or steps in the process (Borgovini et al., 1993). FTA is a top-down, deductive failure analysis used in safety and reliability engineering (Ericson, 1999) and in rebreather diving safety (Tetlow, 2006). It starts from an undesirable outcome, such as "diver ran out of gas" and asks questions how it could occur, which is similar to root-cause analysis (RCA) (Rooney and Heuvel, 2004) used in accident investigation.

Hazard identification precedes development of diving equipment, diving procedures and training processes that are supposed to implement control measures for known hazards. Despite all efforts, mishaps and injuries do occur and raise the question again if everything was done to keep the probability of injury as low as reasonably practicable (ALARP) (Vatn 1998; Kletz 2003).

Risk is a quantitative indication or measure of probability that specific hazards will result with injury or harm (Omen et al., 1997). Some definitions of risk include both severity of potential injury and the probability that it will occur (Moen, 2008). Thus, the risk of an activity such as scuba diving is a compound measure of all present hazards, exposure to them and severity of possible outcomes. In context of diving, we define risk as the probability of injury or death, given a particular set of conditions.

While the risk is supposed to represent a measure of threat, the perception of threat is socially and psychologically conditioned and does not always coincide with the objectively assessed risk (Fischer et al., 1991; Oltedal et al., 2004). Measures of exposure and incidence for diving accidents are not readily available, and thus public perception of risk in diving is influenced by gravity of the most severe injuries and the fatalities. In contrast, the definition of risk in this paper refers solely to the probability of occurrence of such injuries, which is missing in public discourse.

Exposure is the condition of being in presence or subjected to a potentially harmful condition or agent.

The relationship between risk, hazard and exposure may be represented by formula:

Risk = Hazard x Exposure

There is no risk without exposure (and vice versa, there is no exposure without risk). Divers are exposed to dive hazards only when diving. In general, the exposure to dive hazards equates to the number of dives, their duration, the magnitude and the rate of pressure changes. Exposure to some hazards may occur during the specific stage of diving, such as lung overexpansion with consequent arterial gas embolism that occurs during ascent. For some hazards such as drowning, a diver may be exposed during the entire dive.

For decompression sickness, the most often used unit of necessary exposure is a dive. However, the severity of exposure, i.e., the depth, duration and breathing gas that affect the basic process of inert gas loading and unloading, should be taken into account, too. The dive indicates a state of submersion and exposure to pressure, which begins with the descent from the surface and ends with the surfacing. However, the outcome of the dive may be affected by an immediate predive and postdive period, and these should be taken into account. When successive dives follow in a short time interval, their outcome is affected both by previous (residual inert gas, possible acclimatization) and following dives (recompression before symptoms could have developed), and thus a more appropriate unit of exposure may be a dive series. The dive series is usually defined as a succession of dives separated by an arbitrary surface interval, usually less than 24 hours. Various decompression models may call for longer or shorter surface intervals. All dives in a series are affected by similar environment, equipment, procedures, social structure and group dynamic. Often the dive series occurs within a dive trip, conditions of which exert the same influence upon all divers and their dive series on the trip.

In absence of exposure data, the population at risk or the participation in a specific activity is sometimes used, but this does not provide for the comparison of risk between the different hazards. For example, risks of sudden cardiac death in jogging and in scuba diving are not comparable if expressed in number of deaths per number of participants, because joggers jog more often and for a longer period at time than divers dive (Tunstall Pedoe, 2004). The comparison in this case should be done per time of engagement in the respective activity. When the participation is used to define the exposure, the time period must be specified.

INJURIES

In public discussion about diving injuries, terms often used are incident and accident, which imply haphazard nature of injuries and, in the mind of some, indicate fatalistic acceptance and provide an excuse for inaction (Loimer and Guamieri, 1996; Pless and Hagel, 2005).

Incident may be defined as an unintended aberration from a normal dive in which agents of injuries were in motion but the aberration was recoverable and did not cause the injury. The more appropriate term would be a near-miss.

Accident is distinguished from an incident by the outcome: It is an unintended aberration from a normal dive that resulted in injury or death.

The terms incident and accident are rooted in colloquial language; they indicate unintentionality (Girasek, 1999) and are practical one-word terms. A synonym sometimes used is mishap, but it does not indicate the severity of outcome and pertains equally to near-misses, injuries and fatalities. Thus, we prefer to use the terms near-miss instead of incidents and injuries instead of accidents.

Injury is a harm caused to a diver's body (or any living organism) due to transfer of one form of physical energy (mechanical, chemical, thermal) in amounts or at rates that exceed the threshold of human tolerance. It may also result from a lack of essential energy such as oxygen (for example, drowning, hypoxia) or heat (for example, hypothermia) (O'Neill, 2013).

The **accident pyramid** depicted in Figure 1 is a representation of ratios of exposure, incidents (near-misses) and accidents (injuries), which can further be partitioned in various ways to address the range of severity of injuries (Heinrich, 1941b).

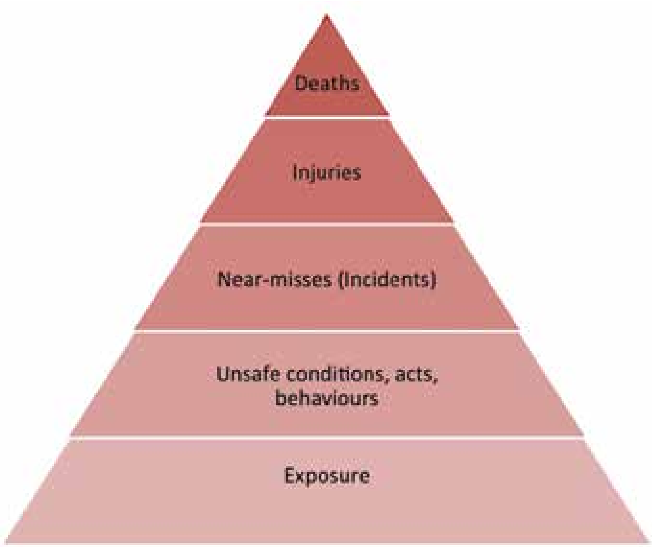

Figure 1. The accident pyramid (Heinrich, 1936), modified by the author (accidents = injuries and deaths).

The basic pattern is similar in all areas of human life and activities, but the numbers may vary. In general, fatalities make the tip of pyramid as the numbers are small, while severe injuries, mild injuries and near-misses are each another magnitude larger and in that order. A superficial look at the accident pyramid may convey opposing messages to different viewers. For fatalists, the pyramid conveys that catastrophic incidents are rare and appear randomly. In such context, no action is needed, and any intervention would be futile. To rational people, the pyramid conveys the message that there is plenty of space for preventive action, which, on the other hand, requires understanding of mechanisms and may be enhanced by the knowledge of causes of incidents. However, some degree of prevention may be achieved by correcting behaviors associated with incidents (unsafe behaviors), such as speeding in driving or exceeding the depth limit in recreational diving, even if we do not know exact causes of injuries.

THEORIES OF INJURIES

Triad of injury. According to the classic injury model, which was a modified model of infectious diseases, for injury to occur (besides being in the environment where the hazard may be present), a combination of forces from at least three sources needs to occur. These sources are the host (in this case the diver), the agent itself (such as sudden pressure change or equipment failure), and the environment in which the host and agent find themselves (body of water such as the ocean, cave, river, or hyperbaric chamber, etc.). A satisfactory equilibrium or adjustment between the diver and his environment leads to an "uneventful" dive or an unchanged health condition as the outcome of dive. If that equilibrium is significantly disturbed, injury may occur. The injury may be caused by the principal action of an agent (e.g., bubbles occurring in tissues due to omitted decompression), by an intrinsic condition of the diver (e.g., undiagnosed heart disease), or as a function of the environment (e.g., cold water), but most often through some combination of the three. The mechanisms involved, such as rapid ascent, entanglement, running out of gas, inhalation of water and similar, may be of secondary interest, while the essential question for injury prevention may be what are the underlying causes that elicit these mechanisms (Gordon, 1949).

Table 2. Haddon matrix applied to diving injuries.

	Human	Equipment	Environment Incl. Social
Pre-event	Entry criteria Training Health Fitness Planning	Design Selection Maintenance Pre-dive check Monitoring	Risk evaluation Safety measures Emergency plan
Event	Self-help Buddy assistance	Redundancy Failure resilience	Surface support Communication
Post-event	Emergency ascent LOC assistance	Breathing protection Flotation Signalization	Rescue First aid Evacuation Treatment

The **Haddon matrix** may be a particularly useful and informative representation of an injury model. The Haddon matrix expands the classic concept of the triad of injury by adding a social environment as a fourth element and by considering three time periods in the course of an injury: pre-event, event (when the agent acted upon the host) and postevent (Haddon, 1968; Runyan 1998). This provides space for intervention in the predive period, which is intended to prevent the agent from reaching the host, and for mitigation, which is intended to treat injuries and prevent permanent health loss or death. The Haddon matrix also emphasizes the significance of the social environment, encompassing the organization of a dive group and safety culture in a broad sense (Runyan, 2003).

There are various other models of injuries and methods of causal analyses (Shapiro, 2008a; Shapiro, 2008b; Shapiro, 2008c; Joffe et al., 2012). Causes of injuries are often multifactorial and can be represented as a multilinear event-sequencing, Swiss-cheese model (Reason, 1990) web of causation (Krieger, 1994) and similar. Events that precede injury often are depicted as a chain of events that suggests that breaking any link in the chain could prevent the injury, an important message for prevention.

QUANTITIVE MEASURES OF INJURY BURDEN

Incidence is the number of new injuries in the exposed population over a specified time period. Preferably it is used as rate. The basic incidence rate is a measure of the frequency with which a disease occurs. It may be calculated per number of exposed (per capita) over a period of time (Formula 1) or per number of exposure units (dives in the case of diving) (Formula 2).

Formula 1.

$$\textit{Incidence rate per population} = \frac{\textit{New cases occurring over a given time period}}{\textit{Population at risk during the same time period}} \times 10^n$$

The **numerator** should include only **new** cases of the disease that occurred during the specified period. The **denominator** is the **population at risk.**

- This means that the people included in the denominator should be people exposed to diving. In practice, we have this information only for some subgroups such as membership organizations (Cumming, 2008; Denoble et al., 2008), professional associations (Richardson, 2010) and similar. The size of the population of divers is usually estimated based on various diving industry data such as issued certifications, equipment sales (Diagnostic Research Inc., 1988), etc.
- The denominator should represent the population from which the cases in the numerator arose.
- The time period usually is one year, and then it is called **annual incidence rate**. If the rate is calculated per number of trainees at specific training courses or per number of visitors to a specific dive site (Hart et al., 1999), it should not be called "annual incidence" and could not be compared to annual incidence.

Formula 2.

$$\textit{Incidence rate per exposure} = \frac{\textit{New injuries (cases)}}{\textit{Number of dives}} \times 10^n$$

- **The numerator** in this case is the number of injuries out of the total number of dives (independent of time frame). Usually it is expressed per 10,000 dives.
- **The denominator** is the number of observed dives. Various surrogate measures such as number of tank fills have been used in lieu of an unknown number of dives (Ladd et al., 2002; Nakayama et al., 2003).
- **Lifetime incidence** is the percentage of divers who experienced the specified injury at least once in their life; it is sometimes used in retrospective surveys (Taylor et al., 2002; Hagberg and Ornhagen, 2004).

INJURY DATA

In general, the incidence of unsafe conditions, acts or behaviors in diving is not known. In the industry it was estimated that for every major injury or death there were 20 minor injuries and 300 incidents (Heinrich, 1941b) or one fatality per 600 incidents (Murrison et al., 1996). A study conducted by ConocoPhillips Marine in 2003 indicated a large difference in the ratio of serious accidents and near-misses. For every single fatality there are at least 300,000 at-risk behaviors, defined as activities that are not consistent with safety programs, training and components on machinery. The ratio of near-misses per number of dives as shown in Table 2 is rarely available (Curtis, 1978; Wadman et al., 2003). The diving environment may be less forgiving, and the ratio of near-misses and morbidity may be higher than in a typical workplace environment.

The earliest publicly available program to report near-misses in diving was the Diving Incidents Monitoring System (DIMS) set by Chris Acott in Australia. (Acott, 1992) This program did not provide data about the population at risk or exposure measures, and thus incidence rates of near-misses could not be calculated (Acott, 1995; 1996). Incidence of mishaps was provided by retrospective (Curtis, 1978; Cresp et al., 2000) and prospective studies (Buzzacott et al., 2009; Buzzacott et al., 2011). Project Dive Exploration provided self-reported incidents (1.4 percent running out of air, 4.7 percent problems with buoyancy, 5.0 percent rapid ascent), and dive computers recorded near-misses (3.8 percent of divers ascending faster than 18.3 $m \cdot s^{-1}$ for at least 6 m vertical ascent) (Buzzacott et al., 2009). The discrepancy between reported and recorded rapid ascents indicates a significance of a subjective experience in the definition of incidents. To increase the likelihood of capturing risk factors, researchers sometimes use surrogate outcomes such as surfacing with less than a preset amount of gas in tanks. These conditions were found in 18 percent of dives, but 10 percent of those divers were not aware of it and thus were not in control (Buzzacott et al., 2011).

Table 3. Incidence of incidents (near-misses) in diving (Survey on Frequency of Various Types of Diving Incidents). Sample: SSAC members; 4,868 dives, representing 148 years of diving experience (Curtis, 1996).

Incident	Occurrence per number of dives
Shared ascents	1/173.8
Rescue of diver starting underwater	1/187.0
Rescue of divers starting on surface	1/202.0
Failure of air supply	1/206.7
Free ascent (from any reason)	1/243.4
Contaminated air supply	1/270.2
ABLJ ascent used	1/486.8
Octopus ascent used	1/486.8
Hypothermia	1/811.3
Illness not caused by diving but manifesting itself unexpectedly during dive	1/2434.0

The morbidity of diving incidents is not known. DIMS estimated morbidity based on self-reported incidents, which range up to 30 percent for equipment-malfunction incidents (Acott, 2003). These estimates may be affected by reporting bias (divers who experienced injury are more likely to report an incident) and by self-indemnification bias, which locates blame in external causes rather than in their own acts and behaviors.

Currently, several systems are available online for incident reporting.

Divers Alert Network provides an online Diving Incident Reporting System (DIRS) in English and Portuguese (www.DAN.org/incidents/). DAN Asia-Pacific provides a similar reporting system (www.danasiapacific.org/main/accident/nfdir.php). In the United Kingdom there are two reporting systems, one by BSAC (www.bsac.com/core/core_picker/download.asp?id=13170) and the other by Gareth Lock (cognitasresearch.wordpress.com/about/).

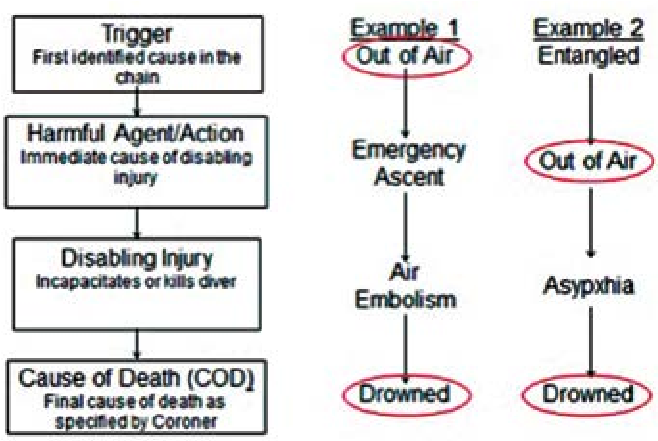

Figure 3. An abridged root-cause analysis.

The incidence of injuries in recreational diving is not completely known because there is no established mandatory reporting within the industry (Hagberg and Ornhagen, 2003; Nakayama et al., 2003). Most complete data are available for the specific diving injuries requiring recompression treatment, decompression illness (Vann et al., 2004b; Lippmann, 2008; Pollock et al., 2008), while the incidence of injuries such as ear barotrauma, which can be treated in primary care or specialized hospitals, is not known. Coding systems for injuries (ICD-9, ICD-10) do not provide distinctive labels for diving injuries unless they are unique to pressure exposure such as decompression sickness (DCS) and cerebral arterial gas embolism (CAGE). These two entities are often reported as decompression illness (DCI), which suits practical needs of medical care but blurs the opportunity to learn more about causation, evolution and outcomes. DCS is dependent on dose of exposure, while CAGE is dependent on the rate and mode of ascent and intrinsic health factors. The incidence of DCS is higher, but CAGE has a higher mortality rate.

The annual incidence of DCS is available from the collection of hyperbaric chamber reports on treated cases as in earlier DAN diving reports, project Stickybeak reports in Australia (Acott, 2003), periodic national reports from various countries (Davis et al., 2002; Lippmann, 2008), membership organization reports (Cumming, 2007; 2008) or from the statistics provided by DAN's Medical Services Call Center as in recent DAN reports (Pollock et al., 2008).

Another piece of missing data for calculation of injury rates is data about the population at risk and exposure to diving. The denominators are often overestimated (Edmonds, 1994), and thus the injury rates are underestimated. The most reliable denominators are available from membership organizations such as BSAC and DAN. Estimates of the population of divers are shown in Table 4.

Table 4. Denominators for injury rates.

Source	Number of divers	Number of dives/ diver/year
BSAC*	38,717	32
DAN insured*	144,400	23
US Census 2000	2,558,000	4
Sport Goods Manufacturers Association 2010	2,732,000	1+
	1,847,000	<8
	386,000	8-14
	490,000	15

*Number of divers/members known.

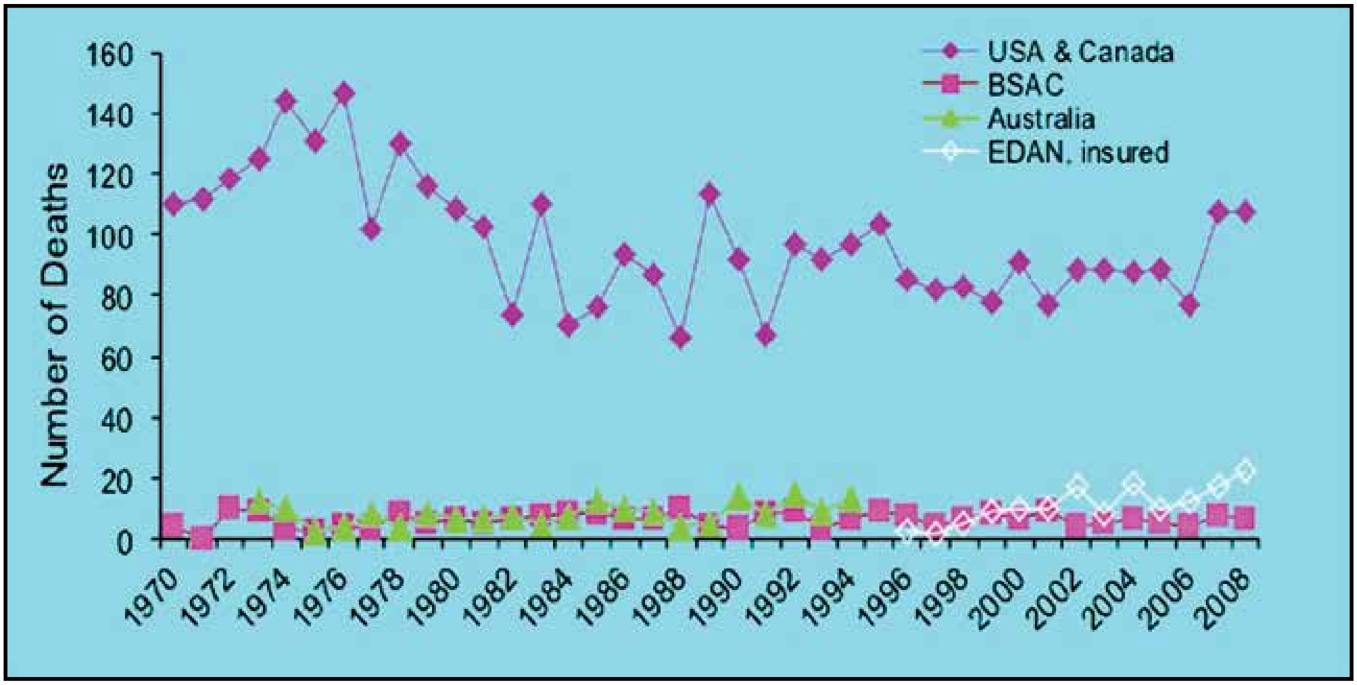

Figure 2. Recreational diving fatalities from 1970 to 2008.

A surrogate for DCS incidence is the DCS insurance claims rate among insured divers (Denoble et al., 2012).

FATALITIES

Diving injuries with fatal outcomes, although not reported to any authority, rarely skip the attention of the media and thus are available for monitoring through the effort of nonprofit organizations such as Divers Alert Network and its large referral network and access to investigative agencies and medical examiners. Most training agencies and membership organizations have established an internal reporting system for injuries that may become a liability, but these reports depend only on internal sources of information. In general, it is possible to compile pretty complete data on diving fatalities. The incidence of recreational diving fatalities as reported by international DAN organizations and BSAC is shown in Figure 2. For more complete data, see the most recent DAN *Annual Diving Report* (Pollock et al., 2008).

For organizations with established populations, it is possible to calculate reliable fatality rates, which are shown in Table 5.

Source	Number of deaths per 100,000 dives	Number of deaths per 100,000 participants/ year
USA Census 2000	0.9	3.6
BSAC members	0.54	14.4
DAN America	0.7	16.4
DAN Europe	1.4	70

Additional sources for injury statistics are participation in distinctive events such as visits to specific dive sites, participation in training courses and surveys of tank fills or, in general, estimate based rates. Selected estimates of fatality rates are shown in Table 6.

Table 6. Fatality rates based on event participation, estimated population numbers or surrogate data.

Source	Denominator	Time period	Fatality Rate per 100,000 dive (95%CI)
Orkney, Scotland	Counted visitors and estimated dives	1999-2000	4
Australia	Estimated visitors an dives	1989	1.7 to 3.4
Japan	Tank fill count		1.0 to 2.4
Victoria, Australia	Tank fill count	1992-1996	2.5
BC, Canada	Tank fill count	1999-2000	2.04
BSAC, non-members British divers	Estimated number of divers	2000-2006	1.03
PADI, training course participants	Registered trainees, recorded dives		0.49

SCUBA FATALITIES INVESTIGATION AND CAUSE ANALYSIS

For establishing causes of scuba fatalities the most important is primary investigation (Vann et al., 2007). This is often missing due to the remoteness of sites were fatalities occur, general difficulties with investigation in aquatic environments, lack of witnesses, inadvertent damage of material evidence by first responders, and lack of trained investigators for scuba accidents. When the primary investigation provides sufficient data, various methods of analysis may be successfully applied to get to the root causes, but with incomplete data most methods fail and causes of individual fatalities may not be established. However, for the prevention of future injuries it is more important to know what most common causes of injuries are than what the cause was in each single case. While the root-cause analysis aims to answer what, how and why it happened (Rooney and Heuvel, 2004), the main purpose of injury surveillance is to establish actionable causes and targets for preventive actions that will result with the greatest possible reduction of fatal injuries.

With that in mind, we have applied an abridged root-cause analysis to the DAN fatality database as is described previously (Denoble et al., 2008). In the first run, all aberrant events, unsafe conditions and possible contributing factors detected in fatality cases were listed. In the next round, it was planned to establish temporal and causal relationships between listed factors in each case. As it was not possible in all cases due to incompleteness of data, we defined minimum common milestones in a cascade of adverse events leading to fatalities: triggers, disabling agents and disabling injuries.

Triggers were defined as the first noticed adverse event that marked the turning of a normal dive up to that moment into an incident. Disabling agents were defined as the events, energy or pathophysiological process that was a decisive, direct cause of injury. Disabling injuries were defined as the injury that rendered the diver unable to function safely in the diving environment or that directly caused death.

The leading trigger is running out of breathing gas. While there are many possible root causes of this adverse event, it may take only a few measures to root out this adverse event and to improve survival in case it occurs.

The three leading disabling injuries making up 85 percent of all fatalities are asphyxia (drowning), arterial gas embolism (AGE) and cardiac arrest. Previous comments regarding running out of air pertain to asphyxia, too. AGE occurs due to a rapid ascent while holding one's breath. The root causes triggering an emergency rapid ascent are many, but providing an independent source of spare air could make the emergency ascent controllable and prevent AGE and death.

When it comes to diving fatalities caused by sudden cardiac arrest (Hayman, 1985), the first intervention that comes to mind is a strict health control and exclusion of those at risk. Unfortunately, the risk of sudden cardiac death is spread among all ages and affects both those with and without a history of heart disease (Goldberger et al., 2008; Bove, 2011). The incidence of cardiac-related death in diving increases with the age of divers but so does the general risk of sudden cardiac death in the non-diving population. Whether there is a surplus of cardiac-caused death in scuba diving and who is at risk remain to be answered by further studies.

CONCLUSIONS

Hazards in diving are many, mishaps are common, but the risk of dying is small. Nevertheless, additional effort is necessary to keep injuries and death in diving as low as reasonably practicable. Most mishaps (and scuba deaths) are preventable. Simple measures such as use of checklist for predive procedures may prevent many deaths. On the other hand, death due to acute cardiac arrest may not be preventable, but cardiac arrest itself is, as has been proven in general population.

To advance dive safety we must continue with injury surveillance including non-fatal injuries. The primary investigation of diving fatalities needs to be improved if we want to establish root causes of injuries. However, when the actionable causes are available, we must not delay development of proper interventions and evaluation of their efficacy since the main purpose of injury surveillance is injury reduction and control. For this to be successful, scientific findings must be shared with the public in a way that helps the public to advance a dive-safety culture. This paper is an attempt to enhance common understanding and thus preventive actions by clarifying terms, measures and numbers used to describe and measure the public problem caused by diving injuries and fatalities.

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ANALYSIS OF RECREATIONAL CLOSED-CIRCUIT REBREATHER DEATHS 1998–2010

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ABSTRACT

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 among open-circuit recreational scuba divers. No particular brand or type of rebreather was overrepresented. 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.

Keywords: deaths, diving accidents, rebreathers/closed-circuit, safety, technical diving

INTRODUCTION

While the principles of closed-circuit rebreathers (CCRs) have been well understood for more than a century (Quick, 1970), 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 miniaturization 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 (Deas, 2010). 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 (Deas, 2010). The information appeared to be derived largely from the Internet forum Rebreather World (RBW; 2011). 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, 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 (RBW, 2011). 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 (Bech, 2010). 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 (Cumming et al., 2010; Deas, 2011; Lippmann et al., open-ended database). Mortality data from recreational scuba diving and other sporting activities were obtained from a variety of sources to provide a comparator (McDonald, 1994; Canberra, 2005; Vann et al., 2007; Bandolier, 2010; Cumming, 2010).

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 (130 fsw), all checks and tests conducted, no wreck/cave penetration;
2. moderate risk, <40 msw (130 fsw), all checks done, wreck or cave penetration performed;
3. intermediate risk, >40 msw (130 fsw), all checks completed;
4. high risk, >40 msw (130 fsw), all checks and tests done, wreck or cave penetration;
5. extreme risk, >150 msw (492 fsw) 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 (Hawkins, 2002).

Finally, failure-probability trees were constructed using the method described by Stone (1989) to attempt to determine the relative risk of mechanical failure of a CCR compared to OC scuba. Further "fault trees" were constructed for each of the major subsystems 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 (Tetlow and Jenkins, 2005).

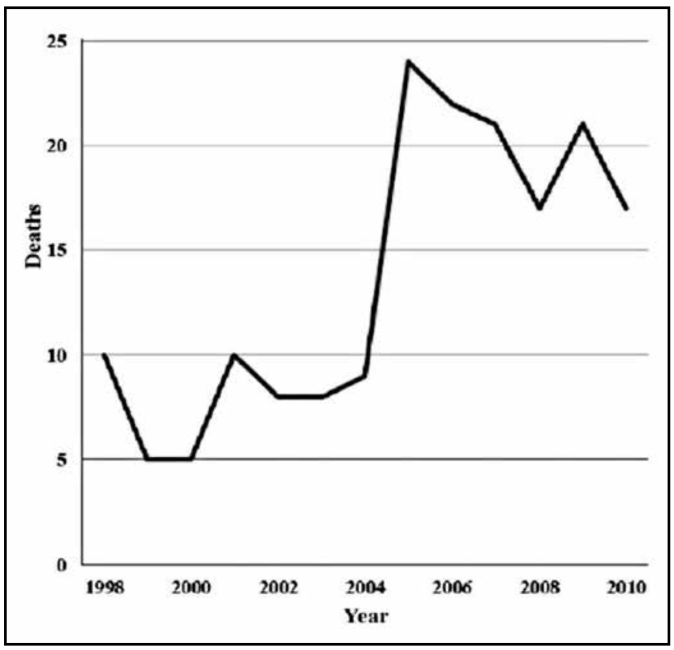

Figure 1. Recreational closed-circuit rebreather deaths by year, 1998-2010.

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 U.S.-based training agencies conducted approximately 18,000 entry-level rebreather certifications with approximately 1,400 per year being conducted between 2001 and 2011 (Barrat, 2010). 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 (Hawkins, 2002; RBW, 2011). 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 (McDonald, 1994; Canberra, 2005; Bandolier, 2010; Dituri et al., 2013; Lippmann et al., open-ended database).

The causes of the 181 fatalities are listed in Table 1. Of the total of 181 deaths, 57 (31.5 percent) had insufficient data to form any conclusions; 80 (44 percent) were attributed to equipment-related problems; 43 (24 percent) 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.

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**	

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, at the time of analysis had 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 overrepresentation 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 percent of units, while in the Dutch survey the proportion was 15 percent mCCRs, accounting for 20 percent of deaths overall and 16 percent 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) (Hawkins, 2002).

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**	

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) (Barrat, 2010), to 360 per 100,000 divers per year, based on 20 deaths per annum and 5,000 units in regular use (Dituri et al., 2013). Others have suggested the total number of rebreather divers lies between 5,000 and 15,000 worldwide (Vann et al., 2007; Barrat, 2010). The data on CCR certifications beyond the initial training skill level would tend to indicate a high retention rate of CCR divers (Dituri et al., 2013). 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 are in current use and that CCR divers conduct approximately 20-50 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 (McDonald, 1994; Hawkins, 2002; Anon, 2007; Canberra, 2005; Bandolier, 2010; Bech, 2010; Cumming et al, 2010; Lippmann et al., open-ended database). 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 eight times less dangerous than base jumping (Table 3) (Bandolier, 2010).

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

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 percent of fatalities but only 4 percent 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 percent of deaths were associated with diving to depths greater than 40 msw (130 fsw), independent of the equipment used. Diving beyond 40 msw (130 fsw) represented 11 percent of dives in this study, equating to a threefold 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 percent) where the victim ran out of gas, a rare problem with CCR divers (Cumming, 2010; Cumming et al., 2010). Despite the perceived simplicity and reliability of OC diving equipment, almost 9 percent of the deaths were attributed to equipment failures. This compares to approximately 30 percent 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 (Deas, 2010). The attitude at that time was exemplified by photos of some of these divers on the wreck of HMHS *Britannic* at 110 msw (361 fsw) without any visible OC bailout (Bishop, 2004). 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 (Hawkins, 2002). 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 percent two-year mortality (Fock, 2007).

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 U.S.-based training agencies do 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 (Lippman et al., open-ended database).

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 (Stone, 1989). 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 modeling suggests that by using a manifold twin-cylinder OC configuration the risk of mission-critical failure could be reduced by elevenfold, whereas reduction in the risk of a single component only resulted in a small overall reduction in risk (Figures 2 and 3).

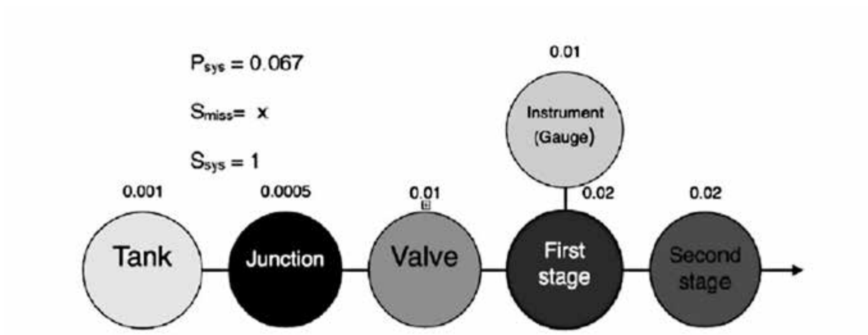

Figure 2. Probability failure tree for a standard open-circuit scuba system.

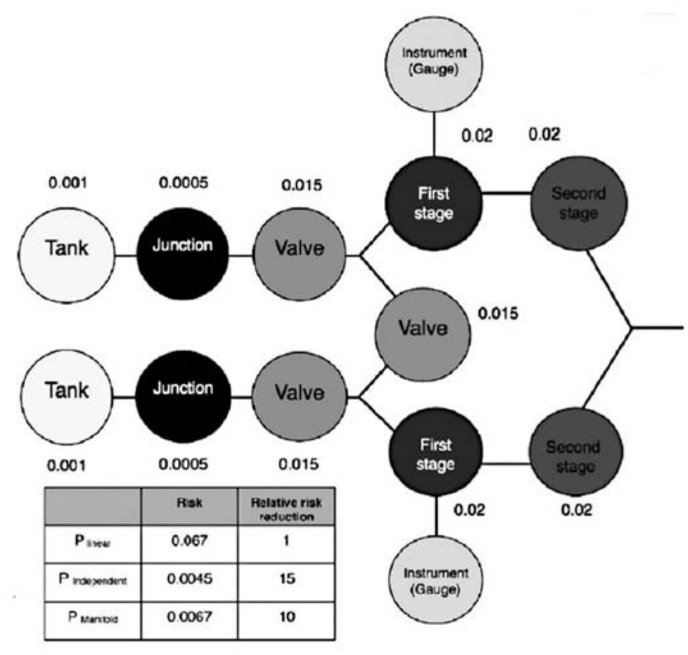

Figure 3. Probability failure tree for an open-circuit manifold twin cylinder.

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 threefold.

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		

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.

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 utilize 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

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 one-third 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

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 predive checks (Tetlow and Jenkins, 2005). 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 prebreathed the unit before entering the water 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 (46 fsw), the diver became aware the CCR's electronics were not turned on. Options at this time included:

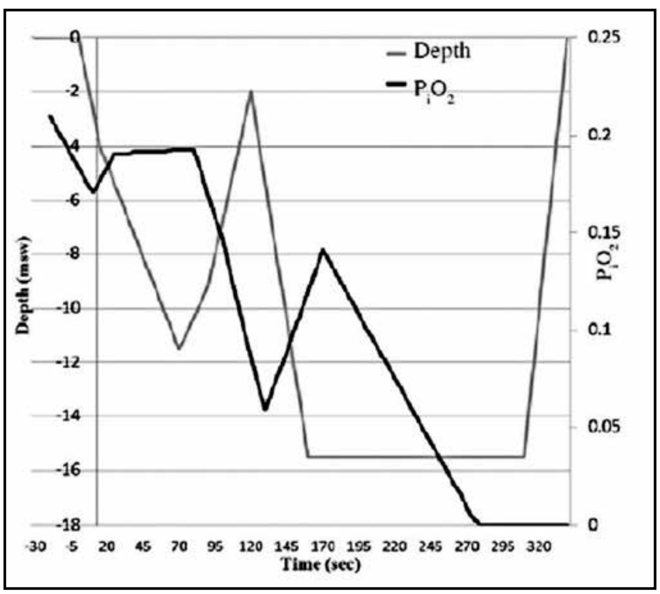

Figure 4. Dive depth and inspired oxygen partial pressure profile of a fatal recreational closed-circuit rebreather dive; unconsciousness occurs 130 seconds into the dive due to ascent hypoxia and failure of oxygen addition because the unit had not been turned on.

- bailout to OC scuba
- ascending to 6 msw (20 fsw) 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 (46 fsw) 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 predive checks to show the CCR's electronics were turned off and in undertaking insufficient prebreathe 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 resited. 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 checklists and of "good design" have been advocated to eliminate wherever possible the chance of human error (Tetlow and Jenkins, 2005). 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 tenfold 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 threefold 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 overrepresented 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 predive checks. While good design can help reduce the chance of human error in maintenance and predive 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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HMS Hermes, *Sri Lanka. Photo by Andrew Fock.*

REBREATHER ACCIDENT INVESTIGATION

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ABSTRACT

In 2006, representatives of rebreather manufacturers, training agencies, government agencies, rebreather users and Divers Alert Network (DAN) met to discuss objectives for rebreather fatality investigations. DAN had collected information on 80 recreational diving deaths from 1998 through 2006 where the diver was wearing a rebreather, but conclusions concerning the causes of these deaths were limited because investigations had been inadequate. The meeting participants pledged cooperation with each other to improve the quantity and quality of collected information. Little has changed since 2006, except that the number of rebreather fatalities has increased. By 2012, the number of fatalities was approaching 200, with 12-15 new fatalities each year. The diving community's efforts to learn the root causes of these deaths have been hampered by a persistent lack of cooperation among stakeholders, a situation that is likely to remain unchanged until medical, equipment and procedural investigations are standardized and various constituencies in the investigative process cooperate more closely. Diving accident investigations should be conducted like aviation crash investigations. In particular, rebreather manufacturers should be permitted to participate in the investigation process at the earliest possible opportunity, at least in an advisory capacity. If the diving community and government agencies are truly interested in enhancing the safety of rebreather diving, the various constituencies must cooperate and share information to the maximum extent permitted by law.

Keywords: rebreather fatalities, rebreather safety

INTRODUCTION

According to published data, there were nearly 200 closed-circuit rebreather fatalities worldwide from 1998 until 2012; currently, there are 12 to 15 new rebreather fatalities each year (Fock, this meeting). "Rebreather fatalities" are classified as "a diver dies while wearing a rebreather," a misleading characterization implying that equipment problems are the cause of many fatalities rather than, as it often appears, diver error or medical issues. In fact, although speculation abounds, little is actually known about the root causes of these accidents because investigations are haphazard and often performed improperly, and suspicion abounds between various stakeholders in the investigative process. This situation hampers efforts to increase rebreather diving safety by identifying the root causes of rebreather accidents and fatalities (Vann et al., 2007; Fock, 2012). Accurate and complete information is required to answer the question: "What is causing rebreather divers to die?" Cooperation between investigating authorities and rebreather manufacturers is essential if accident investigations are to improve. Evidence must be gathered, shared, and disseminated to the maximum extent permitted by law if there are to be improvements in training, equipment, and practice.

WHY SHOULD WE CARE ABOUT ACCIDENT INVESTIGATIONS?

The problem

In 2006, representatives of rebreather manufacturers, training agencies, government agencies, rebreather users and Divers Alert Network (DAN) met to discuss objectives for rebreather fatality investigations. DAN had collected information on 80 recreational diving deaths from 1998 through 2006 where the diver was wearing a rebreather, but conclusions concerning the causes of these deaths were limited because investigations had been inadequate (Vann et al., 2007). The meeting participants pledged cooperation with each other to improve the quantity and quality of collected information. Unfortunately, little has changed since 2006; rebreather fatalities continue to increase, and cooperation between investigating authorities and rebreather manufacturers is inconsistent at best.

The annual number of rebreather fatalities appears to have tripled since 1998, with the total number either at or exceeding 200 rebreather fatalities worldwide and 12-15 new rebreather fatalities each year (Fock, this meeting). The percentage of fatalities involving rebreathers among U.S. and Canadian residents increased from about 1 percent to 5 percent of the total number of diving fatalities captured from 1998 through 2004 (Vann et al., 2007).

Meanwhile, rebreather manufacturers have formed the Rebreather Education and Safety Association (RESA), an association designed to share information, improve training and manufacturing standards, and increase cooperation with investigators in the field. All of the major training agencies have joined RESA as supporting members, and significant efforts to improve training and safety are under way. Unfortunately, cooperation with investigative authorities remains elusive, even while critical information derived from rebreather accident investigations remains the key to identifying the most important points for action to avoid future injuries and fatalities.

Accident investigations — the three track process

Accident investigations follow three parallel tracks: (1) medical-legal autopsies of the deceased diver to look for medical issues causing or contributing to the person's death; (2) determination of procedural issues causing or contributing to the person's death, normally by conducting witness interviews and examining the deceased's training and experience; and (3) investigation of equipment to look for problems or malfunctions causing or contributing to the person's death. Unfortunately, current emergency response and accident investigation protocols for marine incidents are designed to handle the more common incidents occurring on the surface, such as boating accidents and swimmer drownings, and not the less common incidents occurring under the surface, such as scuba diving accidents. This reality, when coupled with the fact that rebreather fatalities comprise just a small subset of overall scuba diving fatalities worldwide (Vann et al., 2007; Fock, 2012), means that current accident investigation protocols are woefully inadequate when it comes to uncovering facts that could lead to a substantial decrease in rebreather fatalities, and a lack of cooperation between investigators and stakeholders in the outcome of the investigation only exacerbates the resulting institutional ignorance.

The typical rebreather fatality investigation today

A review of a typical rebreather fatality highlights the problem with the current state of accident investigations.

On any given weekend, particularly during the summer, a rebreather fatality is likely to happen somewhere in the world. The circumstances are often the same: a well-educated, successful male, aged 35 to 60 and highly experienced as a recreational and often technical scuba diver, dies while wearing a rebreather. The diver is often diving solo or with a buddy using open-circuit scuba equipment, beyond normal recreational diving depths, on a wreck, reef or in a cave. Other divers who are present report that the deceased diver exhibited no signs of anxiety or lack of preparation before the dive; he seemed fine underwater; and they are shocked by the diver's death because he was highly experienced and meticulous about preparing and maintaining his equipment. Typically, the deceased diver was found on the bottom, unconscious, with the mouthpiece out of his mouth, sometime after he failed to return to the surface. Alternatively, he died on the surface after making an unexpected and rapid ascent. Other divers on the scene and the vessel crew are usually unfamiliar with rebreathers; they do not know how to properly record or secure evidence, and they do not know how to interpret information on the rebreather's displays or from audible beeping or flashing lights.

The chances of determining what caused the diver's death worsen once the investigative process begins. First responders arriving at the scene, typically the U.S. Coast Guard or local ambulance and emergency medical technicians (EMTs), are there to provide medical assistance or retrieve the diver and take him to medical assistance — not to conduct fatality investigations. Consequently, first responders are normally unfamiliar with closed-circuit rebreather diving equipment and, indeed, disinterested as their first priority is to render medical assistance or transport the diver to a hospital.

Investigative authorities subsequently arriving at the scene, typically police, sheriff or medical examiner investigators, are also unfamiliar with rebreathers (and possibly even scuba diving). Worse, many investigators do not know how to properly shut down the rebreather and secure evidence. Consequently, accident scene investigations are usually limited to taking cursory (and often conflicting and unhelpful) witness statements from people at the scene, gathering the victim's belongings and (rarely) taking photographs of the equipment. It is not unusual for people at the scene to interrogate the rebreather's electronic controllers and dive computer and inadvertently overwrite data and destroy evidence simply because they are being inquisitive and do not understand how the equipment operates.

Next, the rebreather and other diving equipment are transported to an office and stored until they can be delivered to a local "expert" for an equipment examination. This entire process usually happens without the investigators contacting the rebreather manufacturer to ask for assistance or advice or even to determine if there is anybody nearby who is qualified to perform a thorough and proper equipment examination. Instead, local investigators often avail themselves of the "I got a guy…" network, where the investigator asks around of people he knows until somebody says, "I got a guy who may know something about rebreathers and may be able to help you." Thus, the equipment investigation track now heads down a path that may or may not involve someone who is knowledgeable about the equipment and can provide expert assistance to the overall fatality investigation. Sometimes, the investigator may seek the assistance or advice of the rebreather manufacturer, just as the manufacturer of an aircraft offers expert assistance to the National Transportation Safety Board (NTSB) during an air crash investigation. But, more often than not, the investigator fails to do so. Unfortunately, some investigative agencies are openly hostile to the idea of seeking or accepting expert advice or assistance from rebreather manufacturers, even when stopgap measures are employed to ensure neutrality and maintain proper investigative protocols. Consequently, the institutional ignorance becomes entrenched, even rising to the level of being willful.

Meanwhile, the local coroner or medical examiner conducts an autopsy of the diver's body, often without following the proper forensic medical protocols (Caruso, 2010), such that evidence is not collected (or recognized) that might determine the trigger of the accident. Unless some obvious non-diving medical issue is recognized on autopsy, the cause of death is simply listed as "drowning." Finally, when the rebreather manufacturer learns of the fatality, often within hours, and calls the investigating authority to offer assistance, the offer is met with suspicion and refusal or guarded skepticism and conditional acceptance.

This is the typical scenario in a rebreather fatality, at least in the United States, and it sets the stage for little good. Relevant information is not gathered, evidence is not preserved, questions are not answered, and safety is not improved. For lawyers specializing in prosecuting or defending rebreather lawsuits, this is wonderful as large legal fees are likely forthcoming. But for families of the deceased, currently active rebreather divers, rebreather manufacturers, training agencies, academics, first responders, government agencies, and anyone concerned with diving safety, the results are more than unsatisfactory.

Why should we care about accident investigations? Because the current state of affairs is untenable! Accidents are devastating for families as, more often than not, the victim is the primary breadwinner. Accidents are bad for business, and the consequences of poor investigation include increased litigation costing millions of dollars, loss of cases and higher premiums, and less availability of accident insurance. Accidents are also bad for freedom. For example, the British government has financed the Royal Society for the Prevention of Accidents to consider what might be done to reduce the rising tide of rebreather accidents. Will this also apply to the U.S., European, New Zealand and Australian governments? In summary, if we do not know what the causes are, we cannot make rebreather diving safer. This uncertainty will lead to more accidents and fatalities. If there is to be any hope of determining the causes of rebreather accidents and making rebreather diving safer, all of the stakeholders in the investigative process must establish a surveillance system that improves data quality and completeness, as well as the dissemination of information grained from accident investigations to the diving community.

HOW TO CONDUCT A THOROUGH AND USEFUL REBREATHER FATALITY INVESTIGATION

Tips for first responders

There is such a wide variety of rebreathers on the market, each with its own unique features (Figure 1), that a single investigative protocol cannot apply to all models. A competent investigator needs to be familiar with the model in question or, at the very least, have expert assistance from the manufacturer or its representative so critical data can be retrieved and preserved and relevant procedural and/or mechanical issues can be identified at the outset of the investigation.

If you are the first person on the scene, your primary responsibility is to obtain as many facts as possible. The following tips can be helpful to you, and the information obtained will certainly help the people that depend on you to conduct an accurate investigation.

Figure 1. Some of the recreational rebreathers on the market today.

- Photograph everything, from all angles, many times.
- If possible, take video of the diver's equipment, the scene and rebreather. Even a simple cell phone video can yield important clues about what happened to the diver — clues that may not be readily apparent to the people on the scene with the inevitable emotion that follows a fatality.
- Know what you are looking for and how to look for it.
- Pay particular attention to the displays on the rebreather's electronic controller(s) and the diver's dive computer. Photograph the images and information that appear on these displays.
- Make note of any visual clues or sounds emanating from the rebreather and especially any visual or audible warnings.
- Make note of and photograph the serial numbers on the rebreather and its component parts.
- Make note of any parts that are missing or do not appear to be original.
- Know what you do not know, and do not be afraid to ask for help from somebody more knowledgeable than you.
- Equipment inspection protocols for many different models of rebreathers are posted on manufacturers' websites and on the RESA website. See http://www.rebreather.org/links/.
- Expert advice is always available either directly from the manufacturer or from their local product distributor or approved instructors. Do not be stubborn or afraid to accept assistance when it is offered, but make sure you are getting assistance from the proper parties.
- When writing a report, be honest about what you do not know and explain why.
- When you state an opinion, identify it as such, and state the supporting facts.

- If facts are unexplained, state them, and state why they are unexplained.
- Do not speculate.

Root-cause analysis for scuba diving fatalities

Figure 2. Root-cause analysis of diving deaths.

Scuba fatality investigations can be conducted using root-cause analysis that classifies an incident into a series of four events (Figure 2; Vann et al., 2007). The first event, the "trigger," is the earliest identifiable root cause that transformed an unremarkable dive into an emergency. The second event, the "disabling agent" or "harmful action" is an effect of the trigger that leads to the third event, the "disabling injury." The "disabling injury" either causes death itself or renders an incapacitated diver susceptible to drowning. The final event is the "cause of death" (COD) specified by the medical examiner, which might be the same as the disabling injury or drowning secondary to the disabling injury. It is not unusual for one or more of the four events to be unidentifiable.

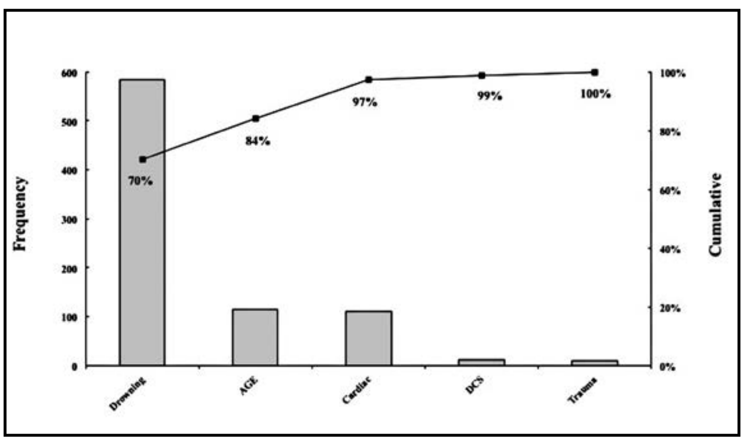

Figure 3. Causes of death in 814 of 947 open-circuit cases (Denoble et al., 2008).

Knowing the COD is interesting but ultimately not helpful in preventing further accidents. Fully 70 percent of all fatalities are classified as "drowning" as indicated in Figure 3 (Denoble et al., 2008). The important question is, "Why do divers drown?" To understand why divers have fatal and non-fatal accidents, investigations must focus on finding the triggers that cause accidents.

Figure 4 illustrates triggers that were identified in 338 open-circuit and 30 rebreather cases (Vann et al., 2007).

Equipment trouble and buoyancy problems appeared more common for rebreathers than for open-circuit breathing apparatus. "Equipment trouble" included both procedural problems and equipment malfunctions that were relatively uncommon. Only three apparent equipment malfunctions were identified: a flooded display, an oxygen supply failure, and an unspecified malfunction at 330 fsw (100 msw) in a cave. There were 11 apparent procedural problems that reflected inappropriate preparation (including maintenance) or equipment operation by the diver: (a) oxygen valve not on; (b) two cases of electronics not on; (c) gases not checked and displays not on; (d) oxygen sensor incorrectly installed; (e) oxygen valve partly blocked; (f) loose connections; (g) predive malfunction of oxygen system in which the diver used an emergency semiclosed mode; (h) a gas leak in the breathing loop and bad oxygen sensor; (i) removed rebreather in wreck to bypass an obstruction; (j) a gas supply valve set to an external rather than internal source; and (k) mouthpiece valve sticking but dived anyhow. Buoyancy problems occurred in seven cases. Four cases appeared rebreather-related involving mouthpiece removal after ascent with failure to close the mouthpiece followed by sinking due to negative buoyancy. Three cases were not rebreather-related and included: (a) tangled in lift bag, pulled to surface, followed by fatal decompression sickness (DCS); (b) drysuit valve failure, blow-up with fatal arterial gas embolism (AGE); and (c) corroded drysuit valve, blow-up from 300 fsw (91 msw), and fatal DCS.

There were a number of problems in the 2007 study related to investigation problems. Triggers were identified in only 30 of 80 rebreather fatalities, and this shortcoming has not changed at all since 2006. Only 3 of 30 triggers were apparent equipment malfunctions

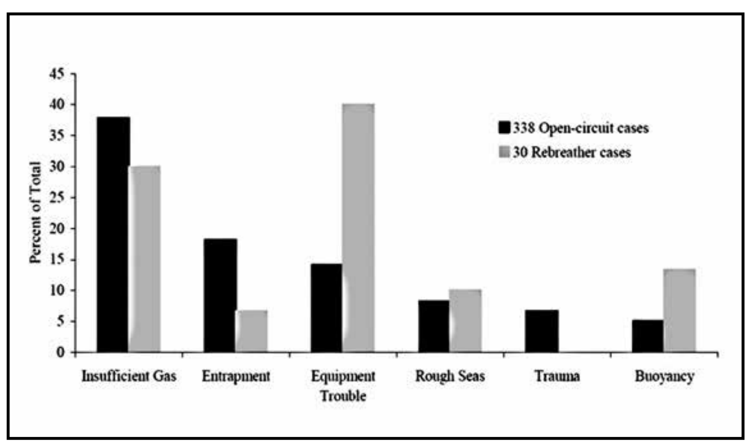

Figure 4. Triggers in open-circuit and rebreather diving fatalities.

(a 1 to 10 ratio), 11 of 30 were apparent procedural problems reflecting inappropriate preparation (including maintenance) or incorrect equipment operation by the diver. The purpose of the 2007 study was to show that it is possible to identify the main factors associated with diving fatalities, but the authors admitted that their information was too incomplete for useful conclusions (Vann et al., 2007).

Cooperation is essential for effective accident investigations
One might rightly ask: What is wrong with the investigative authorities? One problem is that there are no centralized investigative authorities for diving; consequently, there is no consistency in investigations because there are no standard protocols covering all rebreathers and few resources for investigators to access. Moreover, and sadly, there is definite resistance to accepting help from the manufacturers when it is offered — particularly within the U.S. Navy and U.S. Coast Guard, whose stubborn resistance stands in stark contrast to the willingness of the NTSB and the U.S. Consumer Product Safety Commission (CPSC) to cooperate with product manufacturers and engage them at the earliest opportunity. This institutional resistance to engaging with the manufacturers helps nobody.

The success of a quantitative approach to solving the problem of rebreather fatalities relies on the collection of more complete information during the investigative process. This, in turn, requires cooperation of the entire rebreather community — divers, operators, training agencies, instructors and manufacturers — in addition to law enforcement agencies, government agencies and medical examiners. The rebreather community has begun the process of cooperation, with the formation of RESA in 2010 (see http://www.rebreather.org/history/); the organization of Rebreather Forum 3.0 in 2012; manufacturers' publication of unit-specific accident/incident investigation protocols online (see http://www.rebreather.org/links/, http://www.apdiving.com/downloads/resa/, http://www.revo-rebreathers.com/uploads/accident-incident_investigation_guidelines.pdf and http://www.revo-rebreathers.com/uploads/accident-incident_investigation_guidelines.pdf); and more thorough and productive engagement between manufacturers and training agencies. DAN has been instrumental in pushing this effort forward.

Unfortunately, cooperation between investigating authorities and the rebreather community remains inconsistent, partly due to institutional ignorance, which, given numerous efforts to cooperate with investigators that have been rebuffed, can only be characterized as willful. As the old saying goes, "If you are not part of the solution, you are part of the problem."

Equipment inspections — who should do them and how?
Inconsistency in the way equipment investigations are conducted by various agencies is one factor that leads to ineffective accident investigations. However, this problem is easily remedied. Regardless of whom the inspector works for, the following questions must be answered before the inspection takes place:

- How is chain of custody of evidence maintained?
- Who is qualified to conduct the equipment inspection?
- What protocols are used to conduct an equipment inspection?
- Does the investigator know when to ask for help and who to ask for help?
- Will the manufacturer be involved?

The wrong way to conduct an equipment inspection is to use the "I got a guy…" network to find an "expert" to conduct an equipment inspection. Although investigators may be tempted to call on the local dive shop or rebreather instructor for assistance, this generally leads to unsatisfactory results because the local dive shop or instructor may not be familiar with proper equipment inspection protocols. A better practice is to consult with the rebreather manufacturer to determine if the manufacturer can assist with the equipment inspection by providing expert advice or at least recommend a qualified local instructor or service technician who can conduct a thorough equipment examination without destroying evidence.

The manufacturer knows more about the functioning of the equipment and how to use it that anybody else and should be part of the investigation, at least in an advisory capacity. Some investigative authorities are reluctant to involve the rebreather manufacturer in the official investigation due to an unfounded fear that the manufacturer will conceal or destroy evidence if an equipment malfunction is discovered. Indeed, this fear has been encouraged by plaintiffs' attorneys hoping to represent accident victims' families and certain "independent" rebreather experts who are actually connected to these attorneys. As stated earlier, only the lawyers benefit from the uncertainty created by a poorly conducted equipment inspection or fatality investigation. Meanwhile, victims' families, divers, manufacturers and organizations dedicated to improving safety are left frustrated and out in the cold.

Moreover, few investigators realize that rebreather manufacturers are motivated to provide effective assistance to investigations because they have a legal obligation to do so. The U.S. Consumer Product Safety Act, 15 U.S.C. §§ 2051–2084, mandates that product manufacturers have a legal obligation to investigate and report a defect in their product that could create a substantial product hazard, or creates an unreasonable risk of serious injury or death, to the CPSC within 24 hours of receiving notice of an accident (see Appendix A). Rebreather manufacturers routinely conduct internal investigations of accidents involving their products to fulfill this legal obligation and as part of their product development and safety compliance programs for ISO 9000 and/or CE ratings. When a manufacturer offers to assist an investigator in a rebreather fatality investigation, it is not because they are trying to mislead the investigator. Manufacturers want to help investigators, and investigators need the manufacturers' help.

Finally, equipment inspections should not be conducted in secrecy. All of the stakeholders — including the divers' families and manufacturers' representatives — must be involved. If not, investigators would be well advised to videotape the inspection and take numerous high-quality photographs of absolutely everything to ensure that the inspection is conducted properly and anything missed can be caught upon subsequent inspection. To conduct a proper equipment inspection, the process must be transparent to the maximum extent permitted by law.

Compiling and disseminating the final report

Once all of the facts are compiled from the three areas of the investigations — medical, equipment and procedural — they must be presented in a final report. The report should state all facts and opinions leading to the conclusion as to the cause of death, with particular emphasis placed on identifying the trigger(s) of a particular accident. The final report should be disseminated using all available means. The diving community needs to promote a culture where incident reporting and the release of data are the norm, not the exception. Families should be encouraged to release data and autopsy reports to credible organizations (DAN, Rubicon Foundation, BSAC, DIMS, RESA). Coroners and medical examiners should be encouraged to submit anonymous case studies where privacy laws prohibit the release of personal information. Dive computer data, either alone or with the final report, should be provided to manufacturers and credible research organizations. For safety to improve, proper data needs to be collected during the investigative process and disseminated through reports to the people and organizations most qualified to make use of the data to promote safer rebreather designs, improved training and more thorough research.

Suggestions for improvement

It is essential that more useful information is collected through more thorough data-collection methods and that this information is analyzed to determine the root cause of rebreather fatalities and near fatalities.

Stakeholders must increase cooperation with first responders and medical examiners to facilitate effective incident investigation, the collection and preservation of data, and accurate reporting; first responders and medical examiners must seek out and/or accept this cooperation when offered. Manufacturers must be involved in the investigative process. More protocols for effective accident investigations must be developed and distributed widely, with easy public access. Those involved in accidents and accident investigations must be educated about the need to collect facts and preserve evidence, including dive computer data and other relevant information, immediately upon the occurrence of an accident. Eliminate the "I got a guy…" network for finding "experts" to conduct rebreather accident investigations. Instead, certifications should be offered for unit-specific accident investigators. After collection, data must be disseminated to all interested parties (DAN, researchers, equipment manufacturers, training agencies, families and the public) so problems can be identified and addressed more effectively. The rebreather diving community and investigative authorities cannot wait several more years to begin this process. It has to start today.

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Vann RD, Pollock NW, Denoble PJ. Rebreather fatality investigation. In: Pollock NW, Godfrey JM, eds. *Diving for Science 2007*. Proceeding of the American Academy of Underwater Sciences 25th Symposium. Dauphin Island, AL: AAUS; 2007: 101-10.

APPENDIX A.

16 CFR § 1115.12 — Information that should be reported; evaluating substantial product hazard.
(a) General. Subject firms should not delay reporting in order to determine to a certainty the existence of a reportable noncompliance, defect or unreasonable risk. The obligation to report arises upon receipt of information from which one could reasonably conclude the existence of a reportable noncompliance, defect which could create a substantial product hazard, or unreasonable risk of serious injury or death. Thus, an obligation to report may arise when a subject firm received the first information regarding a potential hazard, noncompliance or risk….

(c) Unreasonable risk of serious injury or death. A subject firm must report when it obtains information indicating that a consumer product which it has distributed in commerce creates an unreasonable risk of serious injury or death.

16 CFR § 1115.14 — Time computations.
(e) Time to report. Immediately, that is, within 24 hours, after a subject firm has obtained information which reasonably supports the conclusion that its consumer product fails to comply with an applicable consumer product safety rule or voluntary consumer product safety standard, contains a defect which could create a substantial risk of injury to the public, or creates an unreasonable risk of serious injury or death, the firm should report.… If a firm elects to conduct an investigation in order to evaluate the existence of reportable information, the 24-hour period begins when the firm has information which reasonably supports the conclusion that its consumer product fails to comply with an applicable consumer product safety rule or voluntary consumer product safety standard upon which the Commission has relied under section 9, contains a defect which could create a substantial product hazard, or creates an unreasonable risk of serious injury or death. Thus, a firm could report to the Commission before the conclusion of a reasonably expeditious investigation and evaluation if the reportable information becomes known during the course of the investigation. In lieu of the investigation, the firm may report the information immediately.

USS Apogon, *Bikini Atoll, Marshall Islands. Photo by Andrew Fock.*

U.S. COAST GUARD PANEL

Editors' Note: The following text was summarized by the editors from a transcript of the meeting provided by a court reporter.

Panel Members

LT Jedediah Raskie, USCG, Coast Guard Diving Officer (Moderator)

James Law, Civilian, Office of Investigations and Analysis, Coast Guard Headquarters, Washington, DC

LT Charles Mellor, USCG, Chief of Investigations, Sector Wilmington, NC

MSSD4 Carol Cruise, USCG, Sector Mobile, AL

MST1 Jason Dall, USCG, Safety and Environmental Health Officer, Sector Clearwater, FL

The objective of the panel was to discuss in a public forum what the U.S. Coast Guard (USCG) does in diving-accident investigations, particularly when rebreathers are involved, how this process might be updated, and how the diving community might assist the USCG. Comments from the diving community were encouraged.

USCG investigations involve diving fatalities from commercial and recreational vessels within the jurisdiction of the United States. In accordance with the Boating Safety Act, the cooperates with U.S. states that have significant coastline or inland waterways. Investigations are not to assign blame but to determine who, what, when, where, why, and how a death occurred so that similar future occurrences might be avoided.

USCG investigating officers (IO) move between duty stations that may or may not have diving accidents. A few sectors have popular dive sites. MSSD4 Carol Cruise reported that the USS *Oriskany* in Sector Mobile has many dive injuries and in the last three years five fatalities — two on rebreathers. MST1 Jason Dall reported investigating four open-circuit and two closed-circuit fatalities in 10 years at Long Beach, CA, and Mobile, AL. Recreational diving casualty statistics for 2006-2012 appear in Table 1 to illustrate how diving-accident investigations are distributed across the USCG districts.

Some USCG IOs are divers, but IOs often have no knowledge of diving, and none have rebreather training. IOs have the authority to impound any equipment and vessel logs that appear relevant and to question people with possible knowledge of the events. USCG investigative services may be called in if criminal activity is suspected. Frequently, IOs wait at the dock for the boat to arrive, often accompanied by a USCG escort boat or helicopter. Impounded evidence is returned to the USCG unit, put into storage, and a chain of custody is established and carefully maintained when the advice of outside experts is sought from agencies such as DAN or the Navy Experimental Diving Unit (NEDU). Occasionally, help may be requested from equipment manufacturers, particularly for rebreathers. When an investigation is complete, a written report is sent to headquarters that, upon approval, may be requested by the public under the Freedom of Information Act (FOIA).

The panel agreed that standard USCG procedures for investigating recreational diving fatalities might benefit from

HMS Hermes, *Sri Lanka. Photo by Andrew Fock.*

reevaluation. Panel members and discussants from the audience felt that cooperation between the USCG and the diving community could be usefully expanded since rebreather accidents are occurring more regularly. A standardized operating procedure/checklist for rebreather investigations might be helpful to achieve consistency among the sectors. A list of technical resource contacts was also suggested to include experts local to sectors where diving accidents are common (Table 1). A list of rebreather and dive-computer manufacturer contacts would be useful for providing immediate help to IOs with "black-box" downloading, as this is widely recognized to help ascertain critical events. As the USCG is establishing Centers of Excellence, a Center of Excellence for Diving might be appropriate to provide basic scuba qualification and training in diving-accident investigation that would prepare IOs for diving-accident "strike teams."

Table 1. U.S. Coast Guard recreational diving casualty statistics for 2006-2012. DMI is "dead, missing, and injured." http://marineinvestigation.us

District and Office	DMI
07	155
SECTOR KEY WEST	82
SECTOR MIAMI	35
MSD LAKE WORTH	15
SECTOR ST PETERSBURG	13
DD — FT MYERS	4
DD — MYRTLE BEACH	3
SECTOR SAN JUAN	1
DDE — ST CROIX VI-RIO	1
SECTOR JACKSONVILLE	1
11	62
SECTOR SAN DIEGO	21
SECTOR LOS ANGELES/LONG BEACH	18
MSD SANTA BARBARA	12
SECTOR SAN FRANCISCO	11
05	54
SECTOR NORTH CAROLINA	26
SECTOR DELAWARE BAY (Philadelphia)	15
SECTOR HAMPTON ROADS	4
DD — SFO CAPE HATTERAS	4
MSU WILMINGTON	4
MSD FORT MACON	1
14	36
SECTOR HONOLULU	26
SECTOR GUAM	10
08	30
SECTOR MOBILE	13
DD — PANAMA CITY	11
MSU GALVESTON	4
SECTOR NEW ORLEANS	1
MSU MORGAN CITY	1
01	7
MSD CORAM (Long Island)	5
SECTOR SE NEW ENGLAND (Providence)	1
SECTOR BOSTON (Mass. Bay and NH)	1
09	6
MSD STURGEON BAY	3
SECTOR SAULT STE MARIE	2
SFO GRAND HAVEN	1
13	5
SECTOR PUGET SOUND	5
Totals 2006–2012	**355**

QUALITY ASSURANCE THROUGH REAL-TIME MONITORING

Martin Parker
Ambient Pressure Diving

INTRODUCTION

Rebreather Forum 2 (RF2) was held in 1996. Whether to attend or not was a real dilemma for us. On the one hand we would meet all the tech-diving gurus we had read about in *aquaCORPS*, Michael Menduno's fantastic magazine that enlightened, entertained and encouraged us all to take a fresh look at the way we dived, but unfortunately we could not go because our Inspiration rebreather was just 12 months from launch, and we needed time in the water. The dive trip to the Canary Islands was extremely useful (Figure 1). Some of the design's fundamentals were established such as the layout of the sensors and scrubber, which remain unchanged today. Some of the techniques and protocols that we all take for granted today were established on that trip. We had already dived on trimix, we had tested at QinetiQ, but one of the more interesting finds that we discovered was that a prototype solenoid jammed open on every dive. This gave us first-hand experience with PO_2 control under adverse conditions but was obviously unacceptable. The question was how could we use problems like this to improve the Inspiration? The answer was the quality-assurance (QA) process.

Figure 1. Why we were not at RF2.

QUALITY ASSURANCE

QA includes the aspects illustrated in Figure 2: measuring the dimensions of an oxygen cell molding (center), product design (bottom left), and testing at QinetiQ (upper left) or AP Diving (upper right). The blue machine (upper right) is the first production machine that ANSTI Test Systems made, which we bought in about 1990 for regulator testing. In 2005 we added ANSTI's first 200-m (656-ft) machine in which we test rebreathers in all positions underwater, simulate large oxygen uptakes and can surface at fast ascent rates to make sure the oxygen controller can keep up. We can in fact do all the tests required in the rebreather standards. There are now two more 200-m (656-ft) ANSTI machines, one at Dive Lab and another with the Swedish Navy.

Figure 2. Aspects of quality assurance.

QA can be time-consuming, but it adds value and is practically mandatory for compliance with European Union (EU) standards and maintenance of the CE seal of approval. Only equipment with a CE mark can be legally sold in EU member states. The first step in the QA process is a formal review of a manufacturing facility under a standard such as ISO 9001. Lloyds is and always has been our QA assessor. The assessor wants to see management use QA for improving the process and product: Is there a feedback system from customers and the production line to ensure continual improvement? Are mistakes thrown in the trash or formally reviewed? What about your accidents?

Assessors want you to review your accidents carefully because there is a clear requirement to determine whether the product is to blame and whether improvements can be made to the product, the process or the information given to customers. This process is good for business. Legal problems are most common in the absence of information. Without information, you can bet your last dollar someone will invent an explanation for why your rebreather killed that diver. Lawyers would not be needed in a black-and-white world where everything was known, but they thrive in a gray world of uncertainty. Information is the best protection from lawyers and liability.

The first fatality while using our Inspiration rebreather occurred in May 1998 when a diver became unconscious at 84 m (276 ft) after 14 minutes. The equipment inspection that we attended showed the diver had not properly connected his oxygen cylinder, which meant that his PO_2 would have been falling as he continued to breathe from the rebreather. The diver was also wearing a third-party nitrox dive computer, which set on 50-percent O_2 would beep incessantly when he was deeper than 20 m (66 ft), potentially masking the rebreather's audible alarm. In this instance the dive profile was available from his dive computer, but at the postincident analysis we realized we had to have that data and more stored within the rebreather's memory because we could not guarantee that the dive profile would be available should there be another incident. We decided our rebreathers needed their own "black boxes" with independent data storage.

DATA STORAGE AND ACCIDENT-INVESTIGATION ISSUES

In the UK, an inquest is conducted after most diving fatalities; its purpose is to gather facts, not give opinions or apportion blame. Manufacturers have corporate and moral responsibilities to assist authorities with their investigations. They have a corporate responsibility to investigate incidents and warn existing customers should there be something wrong with the equipment. Sometimes investigators and families of the deceased are concerned that manufacturers will tamper with the evidence, but this is more than unlikely. Tampering with evidence is a criminal offense; if there is a fault with the rebreather, it obviously would not be very smart to add personal criminal proceedings into the mix, so the reality is all manufacturers would be very wary of even being close to the equipment. However, when a rebreather is inspected, it is important to have a manufacturer's representative present to give advice to the investigators — but not touch the equipment.

Some dive computers store data in volatile memory, but this is lost once the batteries expire. Data storage is safer in hard memory so it can be recovered at any time in the future. Our first storage system, the Vision Electronics, went into production in 2005 and stores basic information for 48 dives with detailed information on six hours of the most recent activity, including recording PO_2 and depth every 10 seconds, water temperature every minute and all events, such as warnings or when the diver presses a button, as they occur.

Every user has the capability to download this information using equipment shown in Figure 3. Figure 3a is a download

Figure 3a. Download interface.

interface, and Figure 3b is a USB memory stick with a round connector that plugs into the rebreather. Downloading the data takes about a minute.

Figure 3b. USB memory stick.

In the normal course of events the dive data is stored one dive after another, eventually filling the available memory. During normal dives, "dive-start" and "dive-end" flags are created when the diver leaves and returns to the surface, and these flags are saved to memory. With appropriate analysis of those flags we allow subsequent dives to overwrite the old dive data from the beginning so we can use the memory space again.

However, should the diver be lost and the rebreather not be recovered for some time (six weeks in one case) there is no "dive-end" flag recorded — the diver is simply on a very long-duration dive, so in these circumstances we do not allow the memory to be overwritten from the beginning during the dive as we know on this abnormal dive that we need to preserve the information at the start of the dive. Instead, once the memory is full, the last bit of memory is simply overwritten until the batteries die.

At the equipment inspection, with new batteries installed, the dive data may be downloaded, however great care must be taken: The data download MUST be done early in the equipment examination process. If the unit is dived again or tested in a pressure chamber, the critical dive data will be overwritten. Also, as we record all button-pressing and alarms, if you switch on the unit and attempt to interrogate the handset, the additional data stored may well overwrite the original dive data. It is important, therefore, that rebreathers are stored in a manner recommended by the manufacturer and isolated until a proper investigation can take place.

Sometimes rebreathers are flooded and unfortunately left in a flooded state for some time, and sometimes the power supply may need to be reconstructed to get the download. But again technical know-how from the manufacturer is required — if you reverse the battery polarity, the electronics will be damaged. To avoid catastrophe, contact the manufacturer for help.

Security of the data is key, and encryption will be used in the future to ensure third parties do not tamper with the data. We recommend that equipment-examination officers keep the original data where it is safe from tampering. We have had one instance where a diver and his pet expert demanded to have all our stored data converted to plain English especially for them. This was after we had given them everything that pertained to their dives and predive use of the equipment. Using the UK's data-protection act, they tried to have us reveal how we store information, and you naturally ask yourself: Why do they need to know that? We met with the data-protection authorities and satisfied them with our storage and release of personal information, and they agreed that the information we retained represented our intellectual property and there was no requirement on us to reveal more than we had.

WHAT WE STORE

Figure 4 shows the LogViewer screen that is available to all AP rebreather customers and includes dive profile, PO_2, gas management, and logbook. The black line is the depth with the depth scale reading on the left side with time on the horizontal axis. (You can change easily at any time from meters to feet by going to Tools, then Change Units.) By moving the cursor horizontally, you scroll through a dive and get additional information in the display below: The green box in the center mimics what the handset display shows during the dive. In this example, the PO_2 option has been selected, and information from both oxygen controllers for all three sensors is displayed. The top line of the green box shows the scrubber (middle bar) and battery status. The left end of the bar represents the bottom of the scrubber, and the right end, the scrubber top. Scrolling through the dive, should any warnings have been triggered during the dive, they are shown in the bottom left corner.

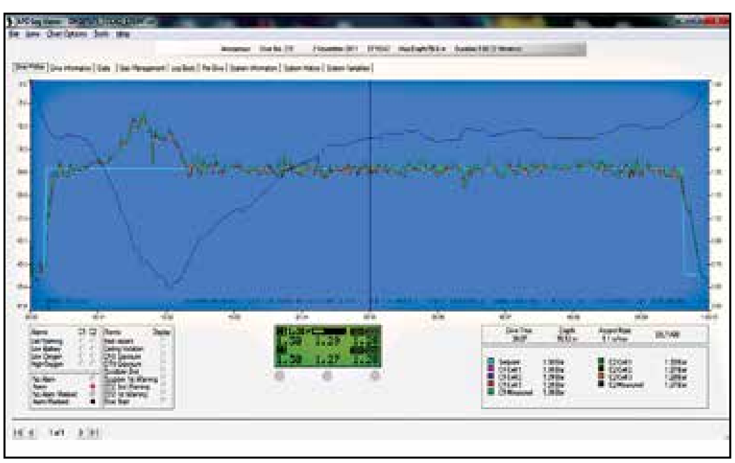

Figure 4. The LogViewer: PO_2 display, setpoint selection, solenoid activity, warnings.

Figure 5 shows the oxygen sensor record from a UK fatality in which there was a big spike in PO_2. This diver made it to the surface, but the questions were what caused the oxygen spike, and did it lead to oxygen toxicity? There were no signs of convulsion, and none of the diver's buddies reported he lost his mouthpiece. We spent a day at QinetiQ trying various scenarios that might lead to an oxygen spike and eventually concluded that manual oxygen injection was the only cause. We have no idea whether the diver pressed the O_2-add button accidentally or on purpose; it does not look as though the high PO_2 was significant in itself, but from a liability point of view it was clearly useful to know the cause of the oxygen spike.

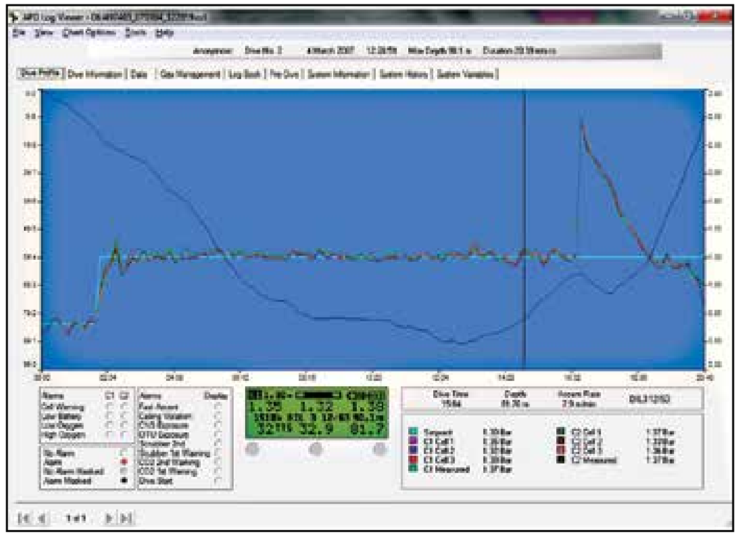

Figure 5. Computer record from a fatality in which there was a spike in PO_2.

While the oxygen spike was not believed to have been a contributory factor in this case, it caused us to add a solenoid activity indicator to the log on the bottom of the blue area in Figure 4. With this new capability, dives may be examined to see whether an increase in PO_2 is caused by the solenoid operation or not.

Figure 6 shows other information available to customers, including the thermal characteristics of the scrubber throughout the dive, the diluent selection at each stage of the dive and, of course, the deco status. One of the great features of the scrubber gauge, shown in the center-top of the handset display, is that the diver can use it during a prebreathe prior to getting in the water to ensure the scrubber is actively removing CO_2. In accident analysis, of course, it is also handy to know whether the diver did a prebreathe or not prior to the dive and of course whether the scrubber was sufficiently active during the dive. If an adequate prebreathe is done the left-hand side of the bar in the green box shows one or two black squares, and if a pre-breathe is not done it will show an empty square.

The scrubber temperature stick in the soda lime bed has been on our rebreathers since 2005 and is a massive boost to safety. Each Temp-stik has eight temperature sensors that measure the extent of scrubber utilization, but only six temperature blocks appear on the diver's display in the green box (Figure 6). The top (last) two blocks are not shown so the diver will not think the scrubber is active when the bed length may be insufficient for CO_2 absorption. At the start of this dive (Figure 6), the scrubber was active except for the first level, which was exhausted and cooling down, which clearly indicates that this was at least the second dive of the day on this scrubber fill.

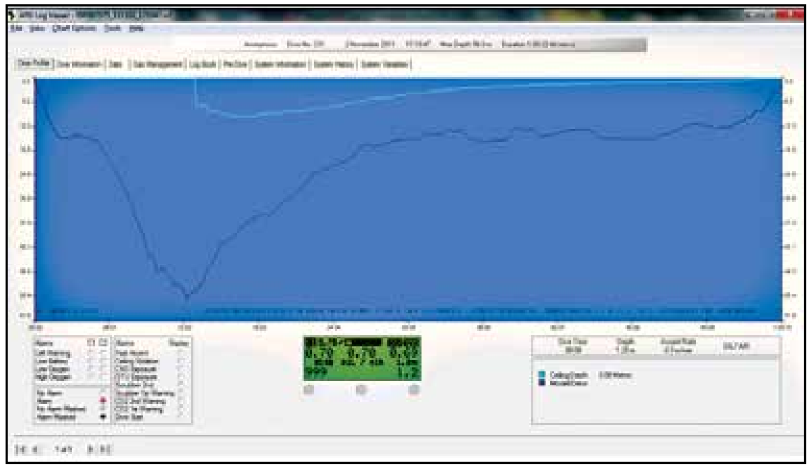

Figure 6. Additional diver information: scrubber status at dive start and through the dive, diluent gas selection and decompression status.

The screen in Figure 7 shows a dive with the cursor on approximately 21 minutes into the dive. The bottom portion of the scrubber, which is indicated on the left of the scrubber gauge, is already blank, which shows us that that portion of the scrubber is already cooling down and it's absorption is virtually spent. This does not happen so soon into the dive on a fresh fill, so for sure this is a second dive or more on this scrubber.

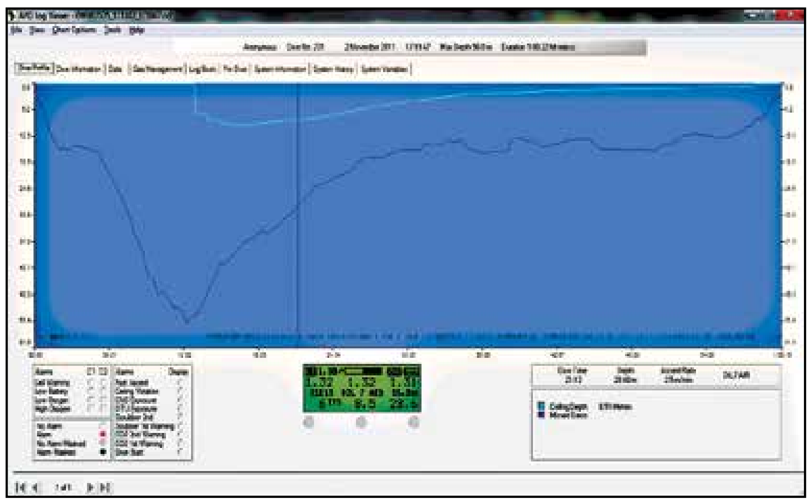

Figure 7. Scrubber status during the dive.

A ninth sensor measures scrubber inlet temperature; while not used for scrubber duration calculations, it can indicate if water may have entered the scrubber should the inlet temperature suddenly change to equal the water temperature. The center of the green box indicates the diluent selection and decompression status. In this case, the diver has six minutes of decompression time before surfacing. Decompression status can be useful during an accident review.

FURTHER CHART OPTIONS

If you click on Chart Options (Figure 8), ambient temperature, battery voltages, cylinder pressure (for future use), and decompression status are shown. PO_2 is the next tab on the user screen. (Scrubber and CO_2 are also for future use). Temperature stick 1 shows all scrubber temperatures throughout the whole dive. This was helpful for understanding why a diver in the Red Sea became unconscious. The PO_2 was fine, but the scrubber temperatures were low, indicating that there was gas-channeling in the scrubber bed, suggesting improper assembly.

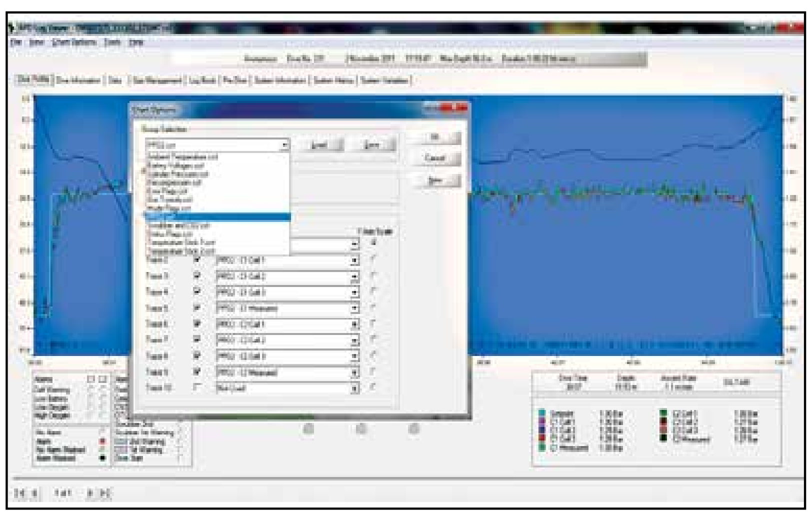

Figure 8. Chart options.

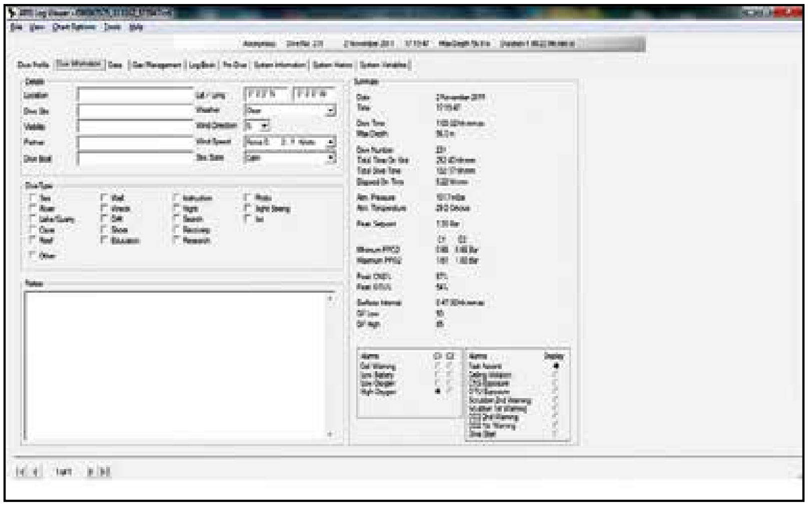

Figure 9. Dive information tab.

Figure 9 displays dive information from the second tab such as date, time of descent, dive duration, and maximum depth. Warnings appear in the bottom right corner — in this case, a high O_2 warning and a rapid ascent warning.

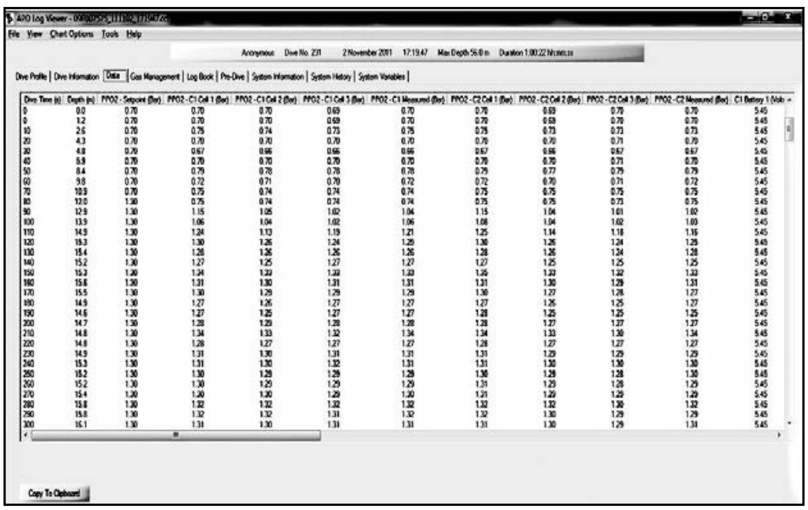

Figure 10. Data page.

Figure 10 is the Data page that shows depth, PO_2, and time values that can be copied into Excel for you to create your own graphs. This can be particularly useful if you have the dive data for two divers, and you can overlay one diver's profile onto the other.

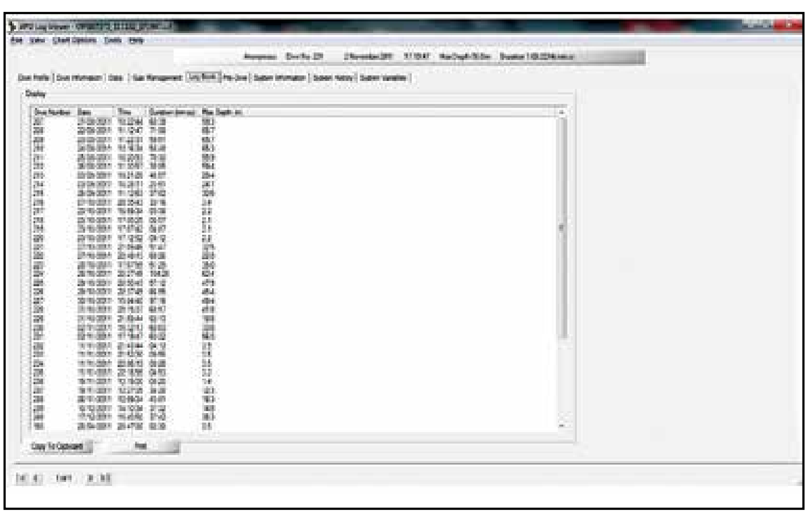

Figure 11. Logbook page.

Figure 11 is the Logbook tab that shows summary information about the last 48 dives.

All of the information until now, with the exception of the solenoid activity, is available to every AP rebreather owner.

From here on, I will show you what else we can see if you send the file to the factory for analysis. Figure 12 is the Predive page that displays information about the status of the unit as it is switched on. It shows the sensor outputs, the battery voltages, the ambient pressure and temperature and the connection status to all the peripherals. It shows us the time and date of switch on and all the sensor calibration information — including whether the diver was told he must calibrate or not and of course whether he did calibrate and if he did calibrate, what the result of the calibration was. The individual sensor temperatures in the scrubber are shown indicating whether the scrubber has just been used. The Predive page is particularly useful during accident investigation.

Figure 12. Pre-Dive page.

Figure 13 is Factory Information that shows the software version and date the product shipped from the factory. Additional system history gives dates of firmware updates. When dive files are submitted, product service information is also available.

Figure 13. Factory Information page.

ACCIDENT ANALYSIS: REAL-LIFE EXAMPLES

Downloaded data is vital to assist investigators in discovering what happened in the event of an incident or fatality, and a full download analysis is only available by involving the manufacturer.

Figure 14 is an example of how data storage helped to clarify the O_2 sensor status when a diver claimed his sensors were faulty. The data indicated no abnormalities; when we examined predive calibrations, Figures 15 and 16 and further back over the previous two weeks of diving, we could see that every oxygen cell calibrated perfectly and their outputs compared precisely to their outputs when the sensors were made at Teledyne and when we shipped them from the factory.

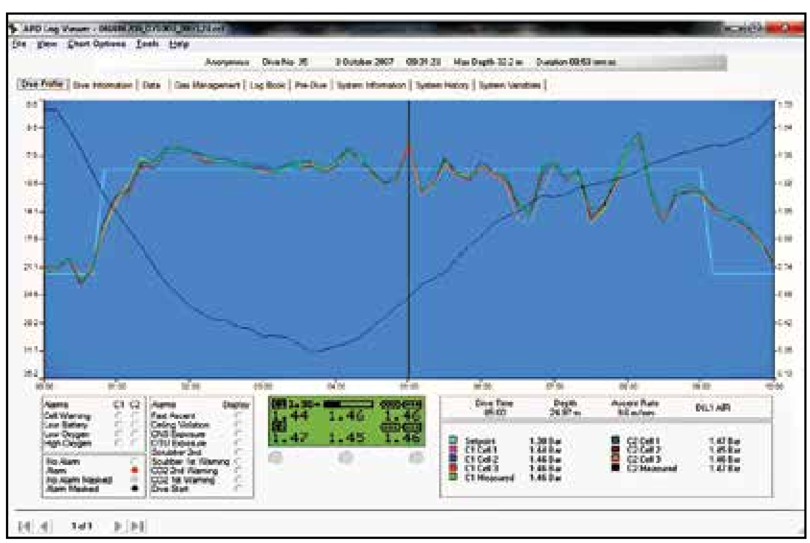

Figure 14. Dive profile for a nonfatal incident.

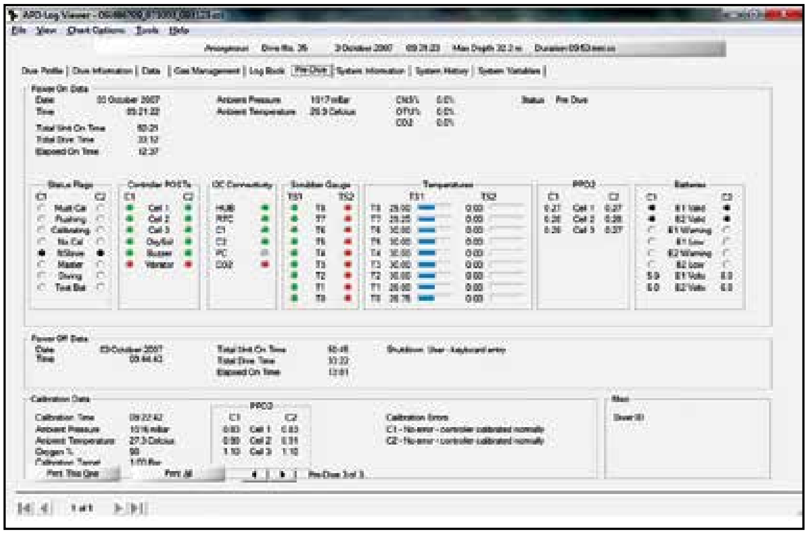

Figure 15. Calibration information prior to dive.

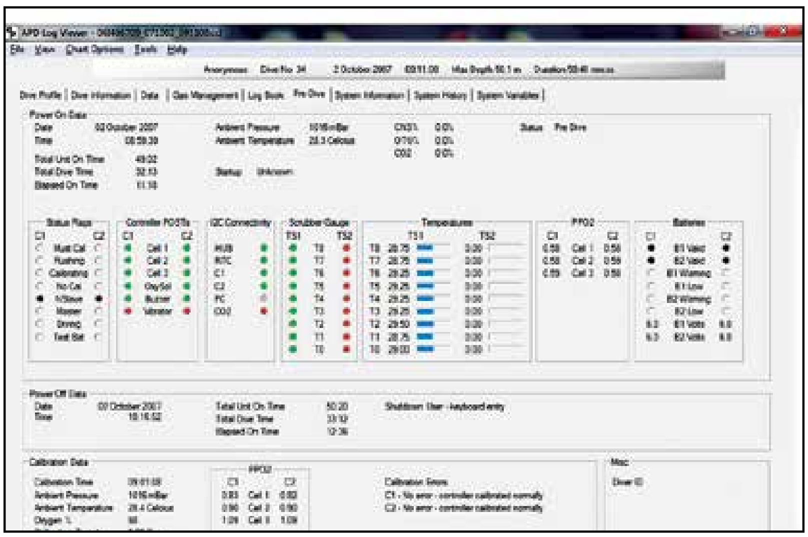

Figure 16. Calibration information for the previous day.

Figure 17. Aquarius Habitat.

A fatality that was particularly challenging to understand occurred near the Aquarius Habitat that is operated by the National Oceanic and Atmospheric Administration (NOAA) off the coast of Florida at a depth of 14 m (46 ft) (Figure 17). In a production, Vision-equipped rebreather the diver cannot switch off the electronics while underwater, but NOAA wanted this capability for when the divers were living in the habitat under pressure rather than diving. We programmed a special button sequence to make this possible. After the accident, a Navy Experimental Diving Unit (NEDU) evaluation indicated the unit functioned normally, so the mystery continued.

In further investigation headed by Jeff Bozanic at the University of North Carolina at Wilmington (UNCW), we were asked to review data downloaded from the Vision Electronics. The screen in Figure 18 is from the dive before the fatal dive. The static depth indicates the unit is in the habitat. During prebreathe, the PO_2 dropped continuously until reaching the 0.4 bar mark, at which the low-PO_2 alarm was activated as indicated in the bottom left corner. The diver had clearly forgotten to open the O_2 cylinder valve. When he did, prompted by the alarm, the PO_2 rose back to setpoint and was maintained by the PO_2 controllers thereafter. From this we can deduce that the diver ignored predive protocols and did not look at the display until the audible alarm caught his attention. He did not tell anybody this had happened, and furthermore when we analyzed the switch off, it appears that the diver just randomly pressed buttons until he achieved what he wanted instead of knowing what buttons to press. It seemed he may not have understood the switch on/off button press sequence, which, while not too important in itself, started to give us an understanding of this diver's experience with this equipment.

Figure 19 is the log screen from the fatal dive. Everything was normal until the rebreather abruptly switched off. The predive information indicated this was done by the user on the handset buttons. We looked into the raw data further and informed Jeff Bozanic's team at UNCW that we had found hundreds of random button presses.

During the fatal dive, the diver had been operating the jackhammer shown in Figure 20. This tool jets out air through its percussion port on land, but when submerged, air is replaced by water, which might jet out with enough focused pressure to operate the buttons on the rebreather handset.

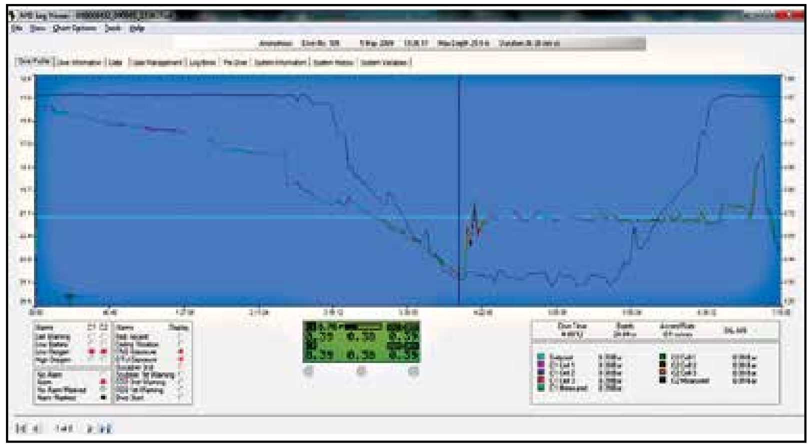

Figure 18. Depth and PO_2 for the dive prior to the Aquarius Habitat fatality.

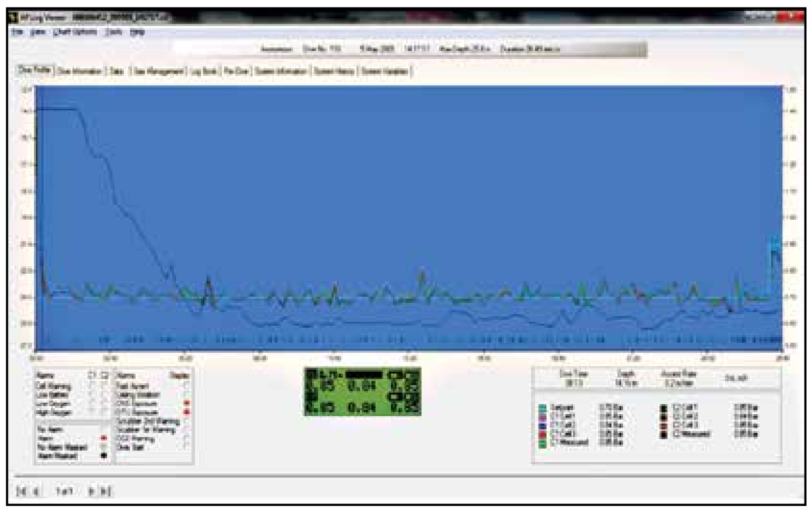

Figure 19. Fatal Aquarius dive.

UNCW tested this hypothesis by holding the handset of an unmodified production rebreather near the percussion port. More than 2,000 button pushes were generated that randomly changed the setpoint, the gases, and other parameters that the diver could adjust underwater. The production rebreather that was tested did not switch off. You will remember the production unit will not switch off underwater, but with fast random button presses it was conceivable that the rebreather we had specially programmed for NOAA may have switched off. This was a plausible reason for the accident.

The important point for me was not that the diver was using a jackhammer — divers frequently use special tools. Rather, it was that he did not check his PO_2 before leaving the bottom. With the extra task-loading during work, a diver needs to be particularly focused and disciplined. There are occasions when you have to stop work and focus on yourself. What is the PO_2 when you first get to the bottom? Look at your display. When you ascend you can become hypoxic and unconscious due to Dalton's law of partial pressures. This has been known since the first days of rebreathers. On semiclosed-circuit rebreathers we flush with fresh gas before the ascent. On closed-circuit, you must check your PO_2 before and during the ascent. This should apply whether you are doing an ordinary dive, making a video, using a jackhammer, or involved in any other task.

The example shown in Figure 21 is from the first of two divers who lost their lives on the same dive. Both were lost underwater for six weeks before recovery, and the dive profile was essential to the investigation for understanding the causes. These were worked out with the help of a video of the recovery, the gases used, gas-consumption estimates and the dive profile. You can see on this download there was a second descent from the decompression level to the bottom, it is believed due to this diver attempting to rescue her buddy, who is believed to have sunk after running out of gas. She had a high-O_2 warning during descent, but that would be normal when the descent is started with 1.3 bar PO_2 in the loop. At the first high-O_2 alarm, she flushed her loop with fresh diluent, lowering the PO_2

Figure 20. Atlas Copco jackhammer.

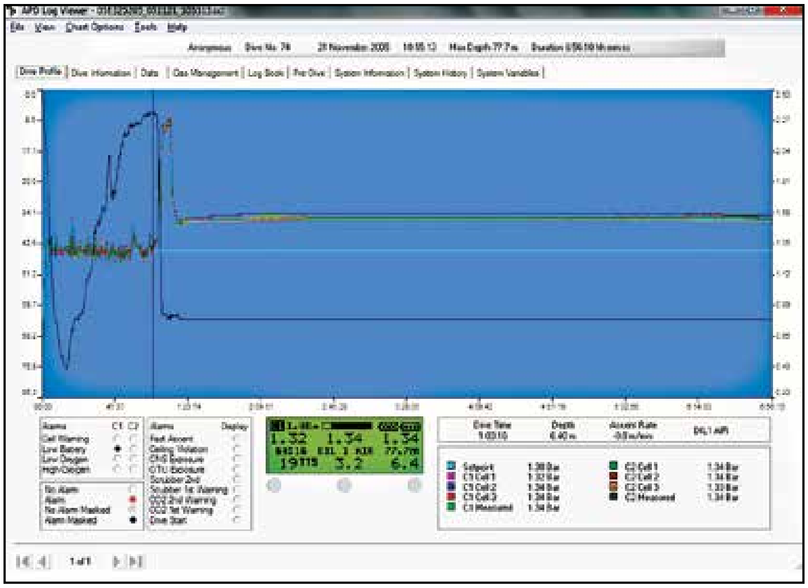

Figure 21. Profile of fatal dive.

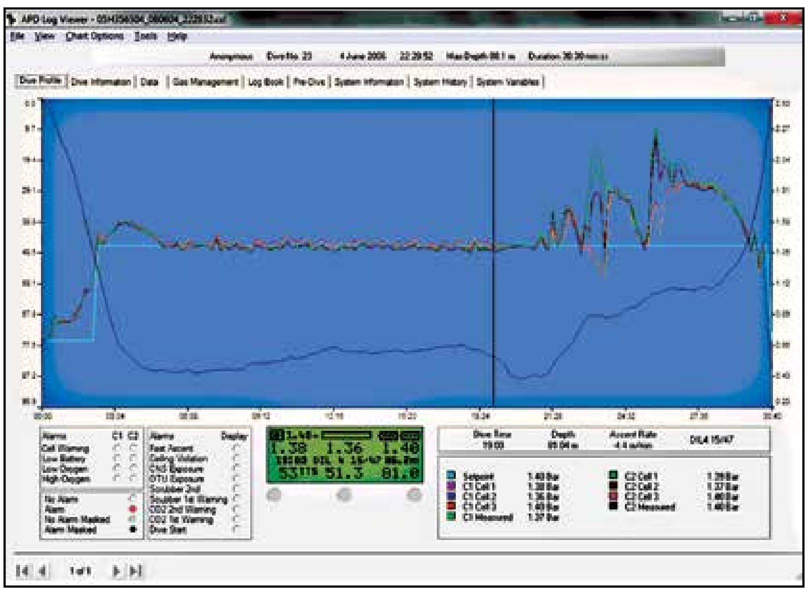

Figure 22. Dive record for a fatality received three years after the event.

but of course as she continued the descent on the high setpoint, the PO_2 naturally climbs; once it reaches 1.6 bar, the machine alarms and warns her. With the second alarm, we can see from the trace that she went onto open-circuit, and with no one breathing from the loop, the PO_2 became very high as she descended further. On the bottom there were what seemed to be quite a few lifts, or attempts to ascend, but after five minutes the PO_2 suddenly fell, indicating that she went back on the loop. The PO_2 then dropped gradually to approximately 1.4 bar commensurate with an oxygen consumption equivalent to a breathing rate of 22 $L{\cdot}min^{-1}$ until she lost her mouthpiece and drowned. The flat line indicated no movement, and data storage continued for seven hours.

Black-box data are important for a thorough investigation, but these data are only part of the story. An investigation team recently sent us a data file for examination and then proceeded to describe the circumstances of the incident. I stopped them from continuing, suggesting it would be better for us to send them the information that we can see in the download, and they can then use that to corroborate what they already know. A proper investigation should glean information from other sources such as physical inspection and eyewitness accounts. To avoid the risk of unintentional bias, those who retrieve the data need only basic information, providing the data analysis is not used in isolation.

Figure 22 is the fatality that Dr. Andrew Fock described in his presentation, but surprisingly we did not receive it until three years after the fatality. This was an 88-m (289-ft) dive, and until 19 minutes into the dive everything looks reasonably normal. Just after this though, the PO_2 traces show large swings; this pattern we have learned is a sure sign the diver is not breathing from the rebreather. In this case we assumed the diver had bailed out to open-circuit and afterward made a fast ascent, missing all his decompression stops. In fact, we were wrong, and this reinforces the point that I would like to make: The download is vital and often tells us how an incident occurred, but this has to be balanced by the accident investigator with other sources of information. In this incident the diver was observed to become unconscious at roughly the cursor location. On this dive we know his PO_2 was fine, but unfortunately there was no temperature-stick information to tell us about the scrubber activity, which would have helped us to determine whether CO_2 was an issue. We do not know if the diver had previously used his scrubber or not, but if he had there is a possibility that CO_2 was a contributory factor. The official autopsy decision was that the diver suffered a heart attack. The remainder of the dive involved recovery in which the buddy initiated a rapid ascent to the surface with the breathing loop no longer being breathed from.

Figure 23 is his dive log indicating that this was his 23rd dive. It was interesting that his first and second dives were to 4.5 m (15 ft) and his third dive was to 55 m (180 ft). However, this was not as enlightening as seeing that his fourth dive was to 104 m (341 ft).

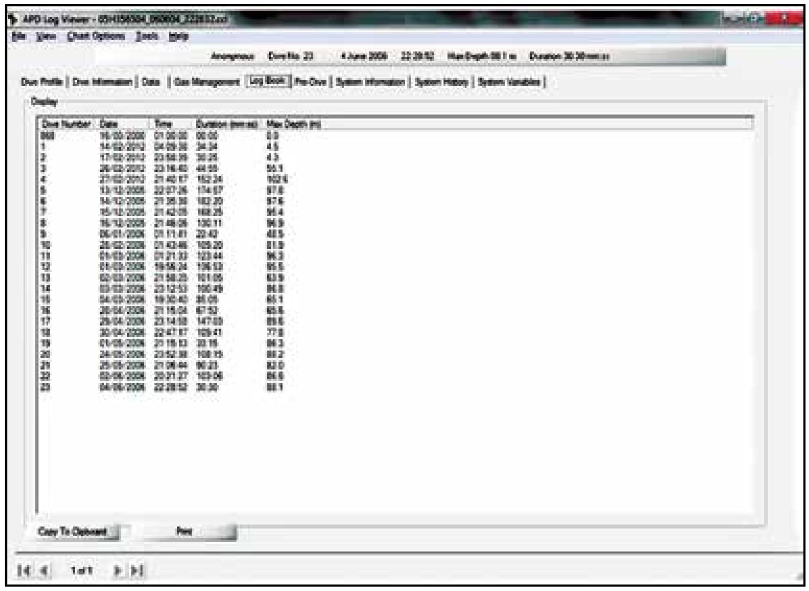

Figure 23. Dive log of the fatal 23rd dive.

CONCLUSION

Many manufacturers were promising rebreathers during the 1990s, but nobody could manage to deliver as was evident during RF2, and it seemed to us that their units were overcomplicated. We decided to concentrate on accurate oxygen control, keeping the Inspiration as simple as possible, and we were able to bring it to market in 1997. With hindsight, however, we realized that data recording would have helped us to explain some of our incidents and fatalities. Not having a recording capability sometimes got us into trouble from 1997 to 2005. In 2005 we introduced the Vision Electronics, which eliminated this problem. When I look at rebreathers today, I regard the quality of their data recording as a measure of product sophistication. For sure, the next generation of rebreathers will have even better recording capability.

Figure 24. AP data recording history.

The take-home message is that data logging is essential. It can save lives, and it can save your company. I would like to see more rebreathers with data recording, and I would like to see instructors teach students how to download the data after dives.

Data recording does not just have to be done by the rebreather's onboard computer. I encourage all instructors to record everything they do and review the recordings with their students to critique their progress. We had a brilliant instructor who recorded everything and had his students sign for every skill they learned in the pool or at sea. One student died three months later through no fault of the instructor or the equipment. Six years later there was a jury trial, and because the instructor had his student sign for every skill completed, the case against the instructor was dismissed because it was clear that he had warned the diver of the inherent risks involved. I would encourage all instructors to follow the same protocols.

POSTSCRIPT: THE *DEEPSEA CHALLENGER*

With the *Deepsea Challenger* project, James Cameron took his submarine to the deepest part of the ocean, the Mariana Trench. We built the life-support systems, main and emergency systems, and for this we took data acquisition to the next step by live-streaming the data from our life-support systems to the submarine's on-board computer, from where it was sent to the surface in bursts every three minutes during the dives. The bottom right corner of Figure 25 shows information transmitted from the deepest point of the dive in which the oxygen level was 17.9 percent, the target level was 18 percent, CO_2 was 0.1 percent, and the depth was 10,900 m (35,760 ft). These data enabled the topside crew to monitor the safety of the environment and communicate recommendations to the pilot. It is pretty clear that in the future live system data will be transmitted between divers as well as diver to surface.

PUBLIC DISCUSSION

DR. RICHARD VANN: Bill Stone challenged the industry this morning to provide rebreather dive data. How would you respond to that?

MARTIN PARKER: Well, that is something that we already do, we already work closely with DAN providing data on a voluntary basis. You noticed Andrew Fock's talk this morning presented data from the DAN analysis, some of which they got from us. Usually we provide just a summary, but I have offered … if they want all the detail, then we will give it to them. We respect the fact that they are an independent organization and do not have an axe to grind, and that is something that we really appreciate. Sharing the data with a body that will use the information properly is no problem at all. Putting the data out publicly, I am not so sure.

Figure 25. Nicky Finn of Ambient Pressure Diving

REBREATHER INFORMATION SYSTEMS

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ABSTRACT

Operational goals of simple measurements have largely been met by rebreather information systems. The systems would be improved by comprehensive logging that would allow substantial recreation of incident events. Lessons are drawn by the safety system evolution in other industries that have similarities to rebreathers. The conclusion is that improvement in the design of the human interface with rebreather information systems, improvements in accident investigation, and the use of checklists are the primary opportunities to improve safety.

Keywords: checklists, data logging, safety program

INTRODUCTION

Information systems for rebreathers are typically built for three purposes: to inform, to control and to record. The goal here is not to review any existing systems but to consider designs for the future and positive industry directions. With closed-circuit diving, most of the problems occur with the way that divers interact with rebreathers, and by improving this interaction safety can be improved. One of the strategies for finding solutions to current design needs is to look at the developmental experience of other industries facing similar problems. The railway and general-aviation industries have struggled with the need to balance safety and operational risks, and by looking at their experiences we can improve rebreather safety.

RAILWAY

The railway industry is useful to consider because it represents the beginnings of formalized safety practices for technology. As trains became more common, several safety issues arose. When people rode trains, they brought their view of the world and their mental model of how trains should work. For example, they assumed that trains would behave much like stagecoaches. Stagecoaches traveled at a rate of 10 mi·h^1 (16 km·h^1), which is how fast a horse can trot (Rolt, 1960). People are capable of running at approximately the same rate of speed, so if they had to step off the stagecoach for some reason, they were able to do so without injury. Trains moved at a higher rate of speed (25 mi·h^1 [40km·h^1]), and it quickly became obvious that passengers would be injured if they stepped off moving trains. The fundamental problem was that passengers did not have an accurate mental model of the automation. Initially the solution seemed obvious. To keep passengers from stepping off moving trains, the trains were closed and locked. The hazard caused by this mitigation was evident in the catastrophe of Meudon when many passengers died after being locked into freshly painted rail cars when the train they were riding in caught fire (Rolt, 1960).

A summary of the death and injuries associated with U.S. railway operations between 1888 and 1892 appears in Table 1. The high numbers described would be completely unacceptable in modern society.

Table 1. Deaths/Injuries of rail workers from 1888 through 1892 (McDonald, 1993). This table is reprinted exactly as published by McDonald (1993).

Year	1888	1889	1890	1891	1892
Road defect	45/153	30/81	61/126	45/101	39/103
Equipment defect	65/35	58/24	30/77	42/65	61/93
Operating negligence	217/573	189/595	337/959	345/930	271/718
Obstructions and malicious	77/163	53/120	60/165	57/114	72/177
Unexplained	69/117	40/119	81/192	61/188	17/113
Totals	473/1041	370/939	569/1519	603/1398	460/1204

Although conditions now are different, it is of interest to comment on the number of accidents reported as operating negligence. While some of these accidents were likely related to intoxicated workers or other clearly negligent behaviors, some also surely involved thoughtful human beings doing their best in difficult situations with dangerous automation. After a careful analysis of the nature of the accidents, it became clear that the coupling gear was a major player in the accidents. The introduction of the automatic coupling gear greatly reduced the number of deaths. These examples demonstrate a similar situation to the rebreather world. It takes time and experience to determine what optimal safety looks like.

GENERAL AVIATION

General aviation, non-commercial flying, is another industry that provides a useful comparison to the problems faced by the rebreather industry. The basic flying license covers visual meteorological conditions (VMC; guided by visual flight rules [VFR]). This means that pilots have to be able to see where they are going to remain oriented in flight. A common advanced license allows flying under instrument meteorological conditions (IMC; guided by instrument flight rules [IFR]). IFR pilots can control the flight solely through reference to onboard instrumentation. Recognizing the hazard of having brand-new pilots flying in zero visibility, a requirement was created that pilots would need 200 flight hours before they could take the more advanced IFR training (Craig, 1993). The U.S. National Transportation Safety Board (NTSB) published a study in 1974 that included a statistical evaluation of the pilots at greatest risk of being involved in a fatal, weather-related accident (NTSB, 1974). The highest-risk pilot had between 100 and 299 flight hours of experience (Craig, 1993). Further analysis indicated that relatively inexperienced pilots were getting into advanced situations while building time to take IFR training. A decision was made in 1986 by the U.S. Federal Aviation Administration (FAA) to reduce the time required to qualify for instrument rating to 125 hours. This seemed to have the desired effect, as the number of accidents for every 100,000 hours of general aviation (flying) dropped from 14 in 1973 to 7.1 in 1998 (Craig, 1993). Although there are still training requirements, there is no minimum time requirement to begin training for an instrument rating for a person holding a private pilot license. In retrospect, a rule that seemed obvious and was intended to reduce accidents was actually increasing accidents. Again, it is time and experience that determines the best way to manage risk.

RISK HOMEOSTASIS

Risk homeostasis considers the human preference for a stable tolerance for risk. Behavior in various situations changes to keep the perceived risk below a comfortable level. Mandatory seat-belt legislation was passed in Canada in 1976 (Sen and Mizzen, 2007). While some may argue that the effectiveness of seat belts is less than optimal, no one denies that seat belts reduce injuries in accidents. The argument is that more accidents or more serious accidents occur due to seat-belt use because people have a risk thermostat and drive faster when wearing a seat belt (Wilde, 1994; Adams, 1995). If this is true, it could translate into a similar effect on rebreather divers.

Divers will eventually deviate from what they were taught during their course. For example, they were undoubtedly taught to run through a checklist and probably did so on every training dive. However, at some point after the course divers may become less diligent with the checklist. If nothing bad happens as a result, their negligent behavior is reinforced. After a period of time and with further reinforcement, the use of checklists can be dramatically lower. This normalization of deviance can lead to significantly increasing the actual risk with little or no change in the diver's perception of risk.

CHECKLISTS

Most people grossly overestimate their ability to notice changes in their environment and underestimate how much the subconscious takes over routine sensory work. Setting up the rebreather becomes a habit or a routine, and over time the subconscious mind takes over. The process can be powered through on autopilot and subtle signals missed and steps skipped when this happens (Jarvis, 2011). Chabris and Simons (2011) illustrate just how much information can be missed when people are focusing their attention elsewhere. They conducted an experiment called "The Door Study," where an actor would walk up to a random test subject and ask for directions. During the conversation, two men carrying a piece of plywood walk between the actor and the subject. While visual contact is blocked, the actor changes places with one of the men carrying the plywood. In half of the tests, the subject continued giving directions without noticing that the actor was a different person wearing different clothes. Chabris and Simons refer to this as the illusion of attention. This example indicates how easy it is for a person to be distracted. Distractions can be fatal during closed-circuit diving because some critical procedures may be skipped.

Checklists offer a strategy to reduce any steps missed due to distractions. Pike (2011) argued that one reason people may or may not use a checklist is because of "perceived or actual peer pressure" and suggested that the use of checklists is the best way to improve rebreather safety. An experiment conducted in 1968 determined that individuals who are faced with "an ambiguous event ... look at the reactions of people around [them] and be powerfully influenced by them" (Darley and Latane, 1968). This suggests that if a diver sees another diver preparing for a dive by running a checklist, he or she may feel the need to do the same. People will decide to act (or not act) in certain ways if they believe that their perceived risk differs than their actual risk.

There is ample evidence in many fields that checklists reduce mistakes. Recent medical research is particularly compelling. In 2008 the World Health Organization (WHO) recognized that the results of surgical procedures across the world would improve if checklists were implemented, as nearly half of all surgical complications are preventable (Haynes et al., 2009). After the checklists were implemented, researchers found that the "rate of complications and death were reduced by as much as 80 percent" (Haynes et al., 2009). The use of checklists resulted in these reductions because the implementation of checklists changed not only standard operating procedure but also the behavior of those performing the surgery (Haynes et al., 2009). If the use of checklists has produced a decrease in the number of surgical complications and deaths arising as a result of surgery, then the use of checklists could have a similar effect on closed-circuit diving.

HUMAN FACTORS

Most of the problems associated with rebreathers occur in the way that divers interact with them, and by improving this interaction, safety can be improved. Researchers at Cranfield University recently created a fault-tree analysis to identify risk in rebreathers (Tetlow and Jenkins, 2005). They categorized the events potentially leading to unconsciousness and drowning (Table 2).

Table 2. Fault-tree analysis of rebreather fatalities (Tetlow and Jenkins, 2005).

End Event	Total Number of Occurrences
Poor training	180
Poor predive checks	147
Stress	78
Poor maintenance	52
Incapacitated	42
"It will do" approach	32
Poor dive planning	29
Mechanical failure	24
Other	16
Total	600

Although the exact categorization of the occurrences is open to interpretation, it is clear that the diver has a large role in the vast majority of outcomes. If the Tetlow and Jenkins (2005) analysis is even close, it is clear that human factors need to be a significant part of the safety design. Table 1 demonstrates that human factors resulted in many railway accidents, just as Table 2 demonstrates that diver error results in many rebreather accidents. This is a behavior problem rather than a design problem, but design mitigations may be available.

REBREATHER SAFETY

The overall goal of rebreather electronics is to maximize the capability and performance of the device while keeping the risk as low as reasonably practicable. There are many kinds of rebreather divers, but in general the capability of rebreathers with regard to depth and time already exceeds the needs of the vast majority of divers. Many of the improvements that will materially affect the future of rebreathers will be in the management of risk and the prevention of accidents.

Risk is always present in life, and as we reduce risk we typically increase costs, increase complexity, or reduce functionality. The risk of rebreather diving may be as much as 10 times higher than open-circuit diving (Fock, 2013). Deciding how much risk is acceptable is answered individually.

ACCIDENT INVESTIGATION

The prevention of accidents needs to be a primary goal as rebreathers move into the mainstream of diving. There are two primary ways to approach the creation of safer systems. In new systems, where no evidence exists, it is necessary to attempt to predict risks and design ways to mitigate the risks. In existing systems, good accident analysis needs to be conducted. After an analysis of this data, the root cause of the accident can likely be determined, and new or modified risks can be discovered. Work can then be done to further mitigate these risks, potentially employing technology to mitigate risks at lower cost.

Despite the fact rebreathers have been in use for decades, there is very little credible civilian data on the root causes of fatal accidents. At present, most of the accident analysis and design of mitigations is done by a small group of people who have collected informal data over the years. Some rebreather fatalities are due to medical issues, some to inattention or carelessness, and others to bad decisions. Manufacturers do not have good analyses on accident root causes, and that makes effective engineering much more challenging.

The primary reason good accident analyses are not conducted is because there is no industry initiative to collect and analyze accident root-cause data. Although virtually every rebreather has data-logging capabilities, these logs are not shared or analyzed with manufacturers, which would be helpful to determine if there were mitigations that could have been provided that may have broken the accident chain.

There are several other reasons why we do not have consistently strong root-cause analyses of rebreather accidents. In some cases there is no specific requirement to investigate. In other cases the investigation may stop as soon as the determination is made that no crime has been committed. Another problem is that first responders and investigators frequently have limited information on how to process the scene, and vital information is lost. Information that is collected may not be publically released, possibly due to a misunderstanding over the benefit of public education or concern over issues of privacy, blame and/or liability. In many countries collected data are privileged in one way or another. Even though lives could be saved in the future, sharing may be discouraged. If the goal of an investigation is to find fault and lay blame, there may be little initiative for impartial efforts by the parties involved. Open discussion of an incident may become guarded if it may later be published in public or even in court.

The suppression of information that could be used to improve equipment or procedural safety is disconcerting but is likely made possible by the relatively small number of participants in the field. Rebreather accidents do not represent a major public health issue. It is necessary for the interested groups to ensure that appropriate analyses are conducted and corrections implemented to improve the community safety. Comprehensive investigation and root-cause analysis of events and free communication of findings is important to address mechanical, cultural, behavioral and training issues. Comprehensive information may not be available for many of the accidents that have occurred, but joint efforts to improve future efforts can improve our understanding and enhance safety.

IMPROVED TECHNOLOGY

Technology has a role to play in the improvement of accident investigation. Several technological directions that are currently being taken in the marketplace will enhance investigation.

One of the developments is the move to digital communications in rebreathers. Virtually all rebreather manufacturers are producing systems now that use digital communications. From serial communications for displays to serial data link control (SDLC), controller area network (CAN) bus and fiber optics, digital communications are part of modern rebreathers. There are several advantages to systems of digital devices in preference to centralized systems. When digital systems are broken into multiple devices an immediate benefit can be simplicity. Instead of having one processor that does everything, tasks can be separated. For example, one processor can manage oxygen injection while another manages the user interface device.

Processing power distributed through a system allows the signal conditioning and control to be closer to the sensors and actuators. These modules then communicate over error-controlled digital communications links. As this design develops, it is easier to create standard interfaces that allow field repairs, device upgrades, and optional functionality. More flexible designs are possible with standard interfaces. New levels of redundancy and monitoring are available as modules become autonomous and mutually suspicious. If the modules are communicating over a digital bus, it is easy to log this data traffic and have a raw data stream that can be captured to analyze system operations.

The capability of microcontrollers and low-cost static memory has improved immensely over the last decade. It is now possible for low-cost and low-power devices to process and store large amounts of data. As rebreather electronic designs get refreshed, much more than dive logs will be seen. It will be common to see comprehensive diagnostic logs from power up to power down. It is critical that system logs change from logs of the dive that start when the dive starts to logs of the system whenever it is activated. In many instances, the behavior of the diver and the system prior to the commencement of the dive can be very important in the analysis of the accident. It is also often important to log the activity after the dive. Changes to the system configuration after the accident can change the outcome of the investigation if they are not logged.

With this data and expert knowledge, it should be possible to reconstruct dives with more accuracy and provide better narrowing of possible root causes. It should be noted that

Figure 1. USS Aaron Ward, *Solomon Islands. Photo by Andrew Fock.*

for these data to be useful, they will need to be shared with the manufacturers. Without manufacturer involvement, it is unlikely that any investigator would be able to interpret the data in a productive way.

At present it may not be possible for the data to actually be used. Some investigative bodies are mandated to not share data for various reasons. In some cases the data have been shared inappropriately, because there was no information available about how to handle it, and sometimes the data are not collected at all. To reduce fatalities and improve mitigations with the tiny amount of data available, a way to collect, store, and analyze data in an impartial setting is required. A system modeled on a medical morbidity and mortality report could be the best solution available. Another possible model would be similar to the FAA/NTSB accident-investigation system. There will still be investigations aimed at assigning blame, but perhaps impartial analyses can also be conducted solely to discover and mitigate any problems.

SUMMARY

Closed-circuit diving is an activity that requires divers to be aware of the risks associated with this type of diving and how to manage these risks appropriately. As Darley and Latane (1968) suggest, for an individual to react appropriately to an emergency, the emergency must first be recognized as such. Closed-circuit divers not using a checklist need to understand that the absence of a checklist is the emergency. Rebreather manufacturers can design mitigations to manage the associated risks, but they will all be defeated if the diver fails to look at the handset. The leaders of this industry have the responsibility to model the use of checklists and to encourage positive cultural change.

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REBREATHER HAZARD ANALYSIS AND HUMAN FACTORS
OR
HOW WE CAN ENGINEER REBREATHERS TO BE AS SAFE AS OC SCUBA

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The Fallacy of the Right Stuff

Bill Storage[1]

Tom Wolff's 1979 book *The Right Stuff* explored the mental and physical characteristics shared by experimental-aircraft pilots and astronauts. The movie version rather accurately portrayed Chuck Yeager as a cowboy with nerves of steel. The mystique of pilots such as Yeager and Charles "Daredevil" Lindbergh has contributed to the attitudes of explorers of other frontiers — particularly mountaineering and cavers — in some ways doing considerable damage. Undoubtedly, personality characteristics such as discipline, situational awareness, and coolness under pressure are highly beneficial for activities in hazardous environments. But other aspects of the "right-stuff" theory have not served us well.

It's worth noting that the right-stuff mystique and deference to its exemplars has also impaired progress in aviation. Lindbergh, misunderstanding the mathematics of system redundancy, equated quality and safety and insisted that quality resulted from "one good engine and one good pilot," i.e., that redundancy meant more parts and hence more likelihood of failure. This resonated with component designers who saw aircraft as assemblies of high-quality parts rather than systems designed from the top down. The notion gave rise to the intuitive but incorrect belief that system safety derived from quality parts. Aerospace engineers were finally forced to surrender this doctrine when the Federal Aviation Administration (FAA) introduced system-level probabilistic risk requirements in 1968. Yeager's surly Southern accent and manner were so imitated by commercial pilots that concern over its contribution to air-traffic control miscommunications arose in the 1980s.

At least two aspects of the right-stuff attitude warrant consideration in rebreather circles. One involves divers' behaviors before and during dives, the other addresses a psychological defense mechanism that emerges after an accident — something akin to survivor's guilt.

In the first case, data such as that presented in HSE Report RR871 reveal that divers' operational violations are the primary causal factor in a large percentage of CCR accidents. The right-stuff belief fosters a sense of invulnerability along with positive illusions such as optimism bias and illusion of control. If explicitly challenged, a diver might deny holding beliefs that his behavior otherwise demonstrates — overestimating the degree of control that he can have over adverse conditions, perception that his skills are vastly superior to those of peers, and belief that those skills exempt him from operational boundaries. Right-stuff mentality in mountaineering also correlates with often-fatal episodes of experience-based complacency.

A second aspect of the right-stuff mentality damages our ability to close the loop from accident analysis to system design. In 1991 I interviewed John Zumrick about social and psychological aspects of cave-diving deaths in Florida. John reported that he commonly saw in a victim's peers the sentiment that when a diver didn't come back alive, he obviously didn't have the right stuff. After the fact, peers were quick to identify specific deficiencies in technique or fitness of accident victims they had known personally. It seems unlikely that if survivors were truly aware of such deficiencies they would not have challenged the diver on them at some point prior to the accident. We suspect that the underlying motivation for such attitudes is an attempt to identify a key difference between the survivors and the victim to justify saying, "That couldn't happen to me because…."

An unfortunate consequence of the tendency of peers to distance themselves from a victim is losing the contribution of those peers in detailing key habits, beliefs, and attitudes of the victim (some of which may have been shared by his peers) that would assist in a comprehensive analysis of contributory factors.

It is indeed likely that certain individuals simply don't possess and can't acquire the right stuff for closed-circuit diving, just as some of us are unfit for dentistry, skiing, or flying. Training and skill-validation criteria should ensure that; if this is the case, it is discovered during certification, not during autopsy.

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There have been several articles in this conference proceeding dealing with mortality statistics for general diving and rebreather diving. The focus of the discussion here is on how to improve the reliability and safety of rebreather systems. The discussion will also include, necessarily, issues of human-machine interaction, diver training and discipline, as the statistics strongly point to these factors in a majority of fatalities involving rebreather diving.

Rebreather Forum 3 (RF3) was timely because we are at a crossroads where we are leaving the postmilitary cowboy era of rebreather diving — where garage shop invention was ubiquitous — to where we are now seeing mainstream training agencies embracing recreational rebreathers. I will emphasize that the nature of this transition is significant as it represents an order of magnitude or greater increase in the availability of these devices to people who were not previously trained and disciplined in technical diving.

Every technical diver who has ever used a rebreather understands the allure of these devices: They offer longer bottom time, no bubbles (and therefore silence when approaching aquatic fauna), dramatically reduced decompression, and vastly increased depth-independent range in a compact device about the same size as an open-circuit (OC) technical-diving kit.

The last point is particularly compelling given that a majority of open-circuit diving fatalities involve running out of air. In open-circuit, a slight miscalculation or panic can mean the difference between life and death. Not so on a rebreather. One of the powerful beauties of a rebreather is that it gives you time to sort out problems underwater.

We are here today largely because of the trends indicated by Figure 1. These show a dramatic increase in annual rebreather fatalities in the last decade. We suspect the trend is a reflection that more rebreathers are being sold today than 10 years ago. Unfortunately there are no exact numbers for either the number of rebreathers sold (due to the proprietary nature of that data) or the number of people diving rebreathers. Nonetheless, the question remains: Can we reduce the fatality rate? We would like to reverse this trend. We should help the training agencies produce better, safer rebreather divers and reduce the potential for human error when using rebreathers. We should help international standards organizations promulgate safe manufacturing practices. But, I will emphasize, we need to do so without stifling innovation.

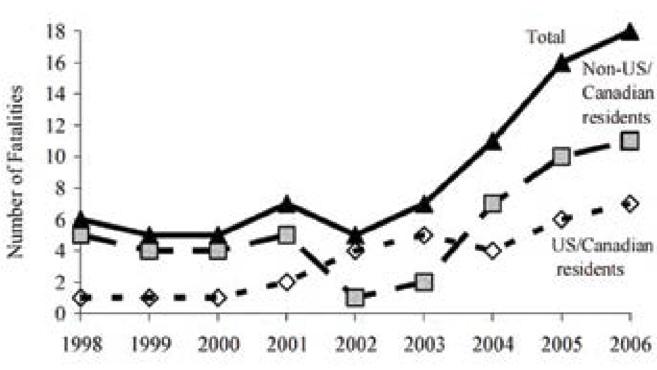

Figure 1. Rebreather fatality statistics, 1998-2006.

What we have seen in the past 30 years is a burst of technological innovation that has greatly benefited the diving experience. But have these innovations also increased the danger to a diver? A couple years ago Jim Tabor wrote a book called *Blind Descent*; and he was famously quoted on *The Daily Show* as saying, "There are 50 ways to die in a cave." Divers Alert Network (DAN) similarly produced a chart (Figure 2) for open-circuit divers identifying 62 ways one can die while on an open-circuit dive. If one analyzes a rebreather, one finds there are many more ways to die (Figure 3) that add on to the

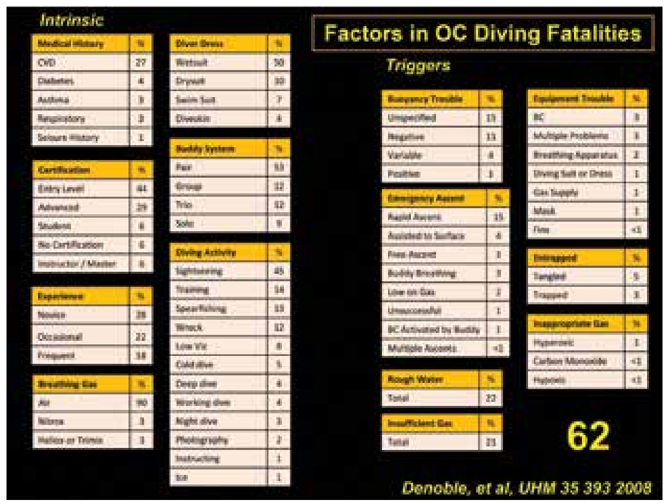

Figure 2. Factors in open-circuit diving fatalities.

Figure 3. Additional diving fatality factors associated with rebreather diving.

open-circuit chart. For example, failure to detect an oxygen leak; failure to conduct a prebreathe; failure to load a sorbent canister. The common wording in most of these is “failure to.” The vast majority of these — especially if one considers the low rate of random component failure — are actually error conditions. The list is long. As one goes down the list, suddenly one starts to feel like an actor in the movie *Forrest Gump* thinking about how many ways to cook shrimp.

When I first went diving it was under very unusual circumstances. I went to a caver meeting at the University of Texas in Austin. There was a guy who got up and gave a talk. He said, “I can use some help. It will involve cave diving.” I said, “When are you going?” He said, “Tomorrow morning.” I said, “But I don’t know how to dive.” And he said, “No problem, show up at my apartment tonight at 7 pm.” I went to his apartment. He came out to the pool and brought a single open-circuit tank with a single regulator, no pressure gauge, and a J-valve. He said, “Put this on your back. By the way, do not hold your breath when you come up.” After a few laps of the pool he addressed me again: “Now I am going to take this chaise lounge chair and put it in water. What I want you to do is take the tank off underwater, push it ahead of you under the chaise lounge chair.” I did that, and when I surfaced he said, “Fine, you are ready to go.”

So the next morning we went off, and I did a 120-m (394-ft) long sump dive, which also was my very first “open-water” dive. The scenario is summarized in Figure 4 (without the benefit of the pressure gauge). There are many people who might question whether that was a good idea or not, but I was young and had no point of reference. Everybody here, with a lot of collective experience, would say it was a bad idea. This is a qualitative, subjective answer. We know it is the correct answer, but why?

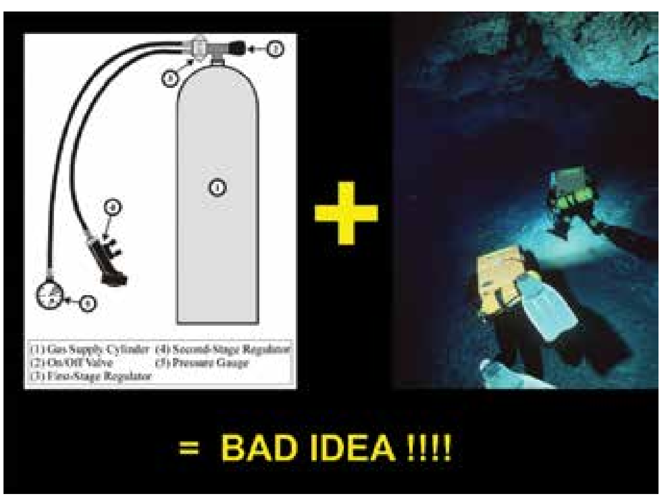

Figure 4. A matter of perspective: Everyone recognizes that cave diving on open-circuit with a single tank and a single regulator is “dangerous.” But can you prove it quantitatively?

The real question is: How do you quantitatively determine if something is “safe.” You say one tank is not enough. Very good, I agree. How many is enough? Consider Figure 5. If I put an open-circuit regulator and pressure gauge on every one of these tanks right here, you would probably say that under normal circumstances there would be a high probability of survival. Maybe not. It depends on the circumstances. If you are in a situation where you might have to be swapping those regulators constantly, and maybe you are doing this at 100 m (328 ft) depth where each of those tanks only lasts five minutes, maybe all of that task management is not so good because you might pick up the wrong regulator.

There are ways to rationally address this problem of assessing safety and reliability. That is why there are professionals in

Figure 5. The intuitive solution to increasing your survival probability on a cave dive is to incorporate redundancy. How much redundancy is “enough” and how much is “too much”?

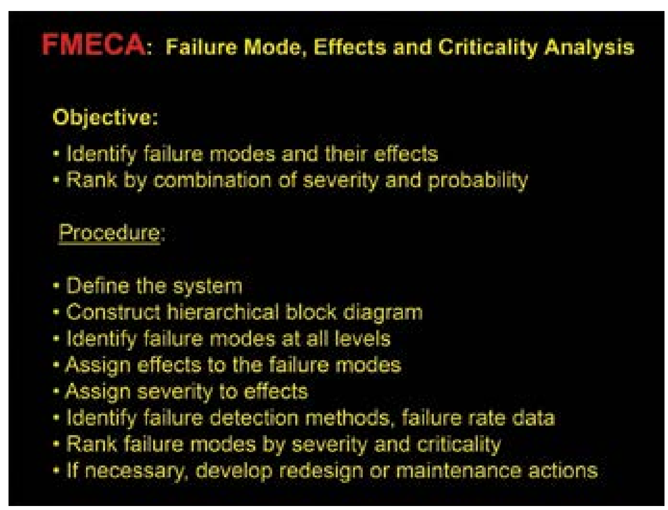

Figure 6. FMECA: a categorical method for assessing the likelihood of criticality of a candidate system design against other designs. It is a required document for rebreather manufacturers seeking a CE approval rating.

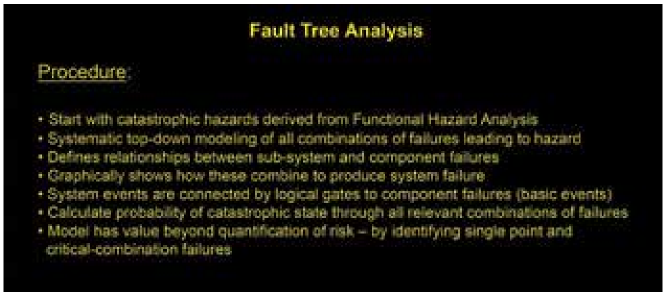

Figure 7. Fault-tree analysis: A numerical probability method for assessing the likelihood of failure of a system in which the components are ascribed individual failure probabilities. It is a useful tool for quantitative comparison between competing system designs.

the aviation industry who make their living describing failure mode effects and conducting criticality analyses (FMECA). I am not going to bore you with the details of those methods, but I will mention a few of their key attributes. When I first started designing rebreathers 28 years ago, I had to write my own pieces of code to do this analysis. One of the virtues of FMECA and fault-tree analysis (Figures 6 and 7) is that they are graphically oriented, and a practiced individual can deduce just by mere sight whether something looks sufficiently redundant.

Just what do we mean by redundancy, and where is it needed? To begin we need to define a few terms. The first is system failure. By this we mean that the portable life-support system has ceased to function and will result in the death of the user unless he/she is able to effect an immediate abort to a safe haven. A safe haven in diving means a pressurized air-filled chamber or the water surface. In the design of life-support apparatus used in hostile environments (e.g., cave and wreck diving) we would like to keep the probability of a system failure to an extremely small value.

In general, the more remote we are from the safe haven, the more unacceptable the prospect for a system failure. In fact, we would like to be able to tolerate a few parts failing and still be able to go on with our job, since in such locations one has likely invested considerable sums of money, time, and effort to train a specialized person or team and place them in the field. This brings rise to the term "mission failure." Here we refer to the state of affairs where the system is still operational but some parts or subsystems have failed in such a manner as to limit the range of the device. In other words, the mission has to be scrubbed because the individual cannot reach his/her objective or finish his/her task because the duration of his/her life-support device has been shortened. While mission failures are certainly not as serious as system failures, it is desirable that they too have a low probability of occurrence.

We can now define redundancy in terms of the failure modes just described. A redundant system is simply one in which a mission failure is possible. To state that more precisely, a truly redundant system is one in which any component or subsystem, no matter how critical, can fail and yet still leave the system in an operational state. It is possible, through careful design rather than expensive parts, to minimize the probability of a mission failure for any given system.

Now consider Figure 8. This presents a graphic means of looking at the survival probability of many systems divers will immediately recognize and a few in between. The "quad-linear" architecture (four tanks with independent regulators and pressure gauges — think two backmounted K-bottles and two sidemount tanks) has a tremendous survival advantage over a simple single tank. The survival advantage (the first data column in Figure 8) is the inverse of the "system failure"

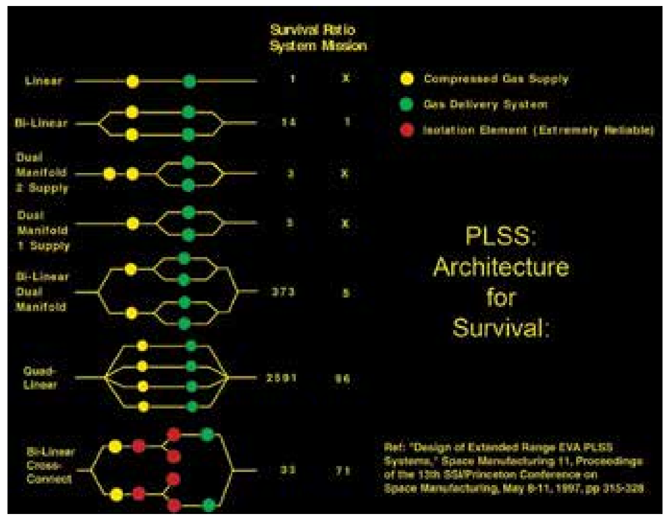

Figure 8. A fault-tree analysis of several common open-circuit scuba systems and variants thereon showing two metrics: system survival ratio and probability of mission success.

probability. A higher number in the left column of numbers indicates a higher numerical probability of survival. A similar metric for mission success probability is given in the right-hand column in Figure 8 (calculation of this number is more computationally complex — see the reference listed below for details).

Figure 8 was generated for the case of simple open-circuit hardware. There is a limit to what you can do with open-circuit equipment. Figure 5 illustrates those limits. That was back in 1984, and the image was of Rob Parker carrying eight tanks with him and two on his back at a dive site with multiple sumps called the Cueva de la Pena Colorada on the Huautla Plateau. We started off with 72 tanks. By the time we got through six underwater tunnels we had enough gear left for two divers to make a single push in Sump 7, and then you had to pull out all those expended tanks and start the process again.

Toward the end of that project we were sitting around base camp one afternoon, and Noel Sloan and John Zumrick began a conversation that well could be considered the starting point for the development of rebreathers for technical diving. We could not get any further with the technology we had even though we had the first composite fiber high-pressure diving tanks, which we were running at 6,500 psi (448 bar). They weighed about seven and a half pounds and carried 105 cu ft of gas. Noel complained to John that the problem was that we just could not pump enough gas into the tanks to get through Sump 7. I offered that we could bypass that problem if only we could change the laws of physics. John looked over at us and said, "Well, you guys are not so far off." And Noel said, "About pumping more gas or violating physics?" John said, "Well, have you ever heard of rebreathers." I had not. Neither had Noel. John was, at that time, on his way to becoming the chief medical officer at the Navy Experimental Diving Unit (NEDU), and he knew a lot about this stuff. That was the beginning of the transition to closed-circuit (CC) for cave dives.

At that time there really was not much available in terms of accessible rebreathers. There were the military units, and there was what the National Aeronautics and Space Administration (NASA) had developed for the space program (Figure 9). You might think: What does that have to do with diving? The space shuttle's extravehicular activity (EVA) Primary Life-Support System (PLSS) — the life-support backpack for the spacesuit — appears very complex. But inside it is basically an oxygen rebreather and a valve that will give you 10 minutes of open-circuit bailout. If the oxygen rebreather fails by any means — which it did on the first attempt to use it in orbit back in 1982 because of a fan that would not blow the air through the helmet — you had 10 minutes to get to the air lock. The spacesuit cost several million dollars of taxpayer money. Zumrick famously quoted at the time, "If you only gave me half a million dollars, I could design you a suit that did not work." But the issue of bailout on a spacesuit PLSS was real. You cannot "buddy breathe" in that situation — a situation common to present-day rebreather diving. If you did not get back in the hatch in 10 minutes there were serious consequences. If you lose a diver, there are diving-accident investigations. But if you lose an astronaut, you shut down the entire space program. Would a cave diver work with only a 10-minute bailout?

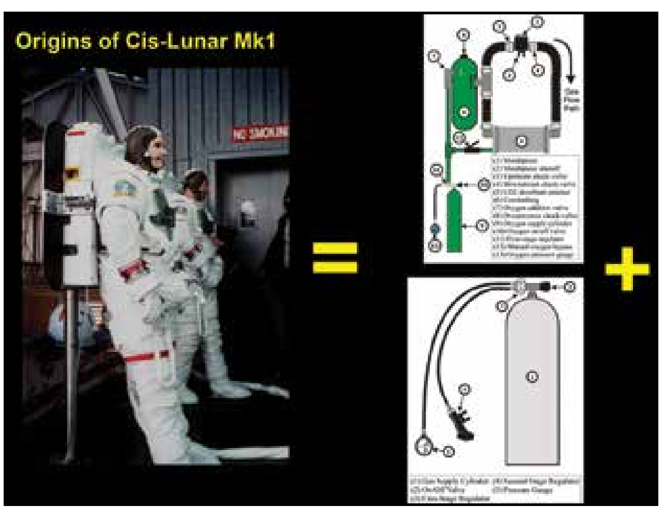

Figure 9. The space shuttle extravehicular mobility unit (aka "spacesuit") and a simplified schematic of its internal life-support systems, which consist essentially of an oxygen rebreather and an open-circuit bailout.

So we started to think, how do we build a system from that knowledge — this was back in 1984 — that would be safe enough for cave diving? Figure 10 shows the architecture that resulted from several years of work. This was the tightest possible configuration then that would allow you to utilize dual gas supplies, dual breathing loops, and be able to access both gas supplies and both absorbent beds from each side of the rig. It was not the kind of thing that you simply picked up with one arm and threw on your back and went diving. It took a dolly to wheel it out to the head pool of Wakulla Springs in December 1987, where we did the initial test dives. The person in the image in Figure 10 is Sheck Exley.

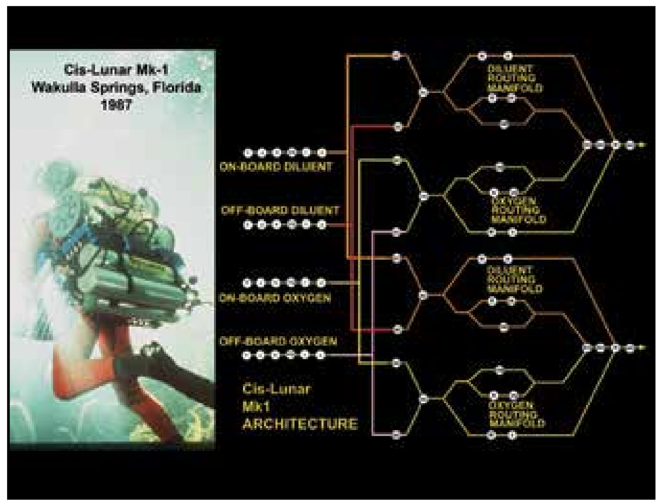

Figure 10. A fault-tree diagram for a fully redundant rebreather (at right). At left, early testing of the Cis-Lunar Mk1 redundant rebreather known as "FRED" (Failsafe Rebreather for Exploration Diving).

Over the next 12 years we successfully honed that machine down to a smaller and smaller device (Figures 11 and 12) until we got a chance to return to Wakulla Springs in 1999, mainly for the purpose of creating the first three-dimensional cave map. From the standpoint of a rebreather, we wanted something much simpler than what was tested there in 1987. We maintained the idea of dual gas supplies: twin onboard oxygen tanks and two large-capacity sidemount diluent bottles. But for simplicity we went with a single rebreather core (a Cis-Lunar Mk5).

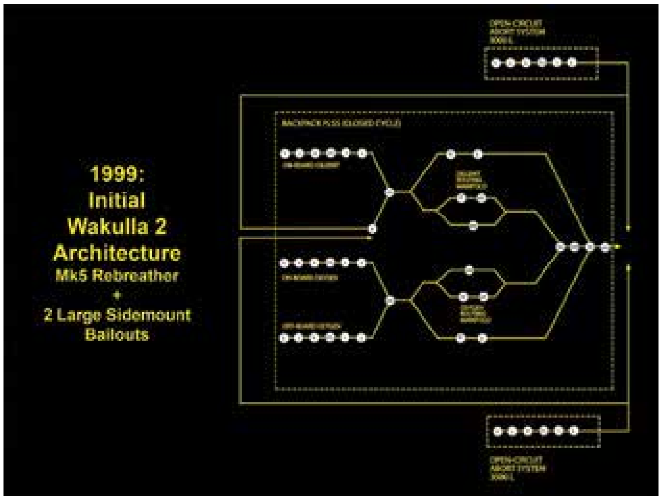

Figure 11. A fault-tree diagram for a partially redundant rebreather designed for the Wakulla 2 project in 1998. The system used dual gas supplies routed to a single rebreather with a manual backup control system.

Figure 12. The Cis-Lunar Mk5P rebreather used during the Wakulla 2 project.

Figure 13. Typical deployment of a 3D mapping team during the 1998-1999 Wakulla 2 project. Each diver carried a single back-mounted closed-cycle rebreather with dual gas supplies and redundant propulsion vehicles.

To reduce transit risk on that project everyone on the mapping teams used dual propulsion vehicles (Figure 13). We further reduced risk by recovering the divers at 30 m (98 ft) depth with a diving bell. The rebreathers were brought to the surface by a support diving crew that would hand them over to mission-control staff who would then download the decompression tissue tensions from each rig. A chamber decompression profile was then calculated (using Decompression Computational Analysis Program [DCAP]), and for the next 12 hours or so the dive team would decompress in a controlled chamber (Figure 14).

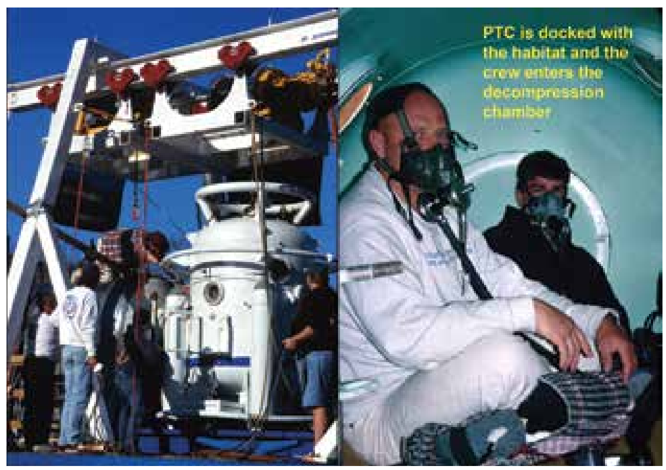

Figure 14. Decompression risk was reduced during the Wakulla 2 project by recovering the dive teams at a depth of 30 m (98 ft) using a transfer capsule that transported the dive team under pressure to a surface-based decompression chamber.

So that was 1999. What most people do not know is that we carried out a number of very interesting life-support experiments on that project. The fundamental issue behind both was that if you are diving deep you do not want to bailout to open-circuit if you can avoid it. In fact, we had to set limits on all of those dives dictated by the range of an open-circuit bailout string that had been meticulously set in each tunnel at Wakulla.

The ideal rig for exploration, science, and deep diving is a dual rebreather. I realized this back in 1984, and it is why the Cis-Lunar Mk1 was designed the way it was. But it was too complicated and bulky in 1984. The bottom line is that, for any type of ultimately committing dive, you want the ability to bailout to closed-circuit.

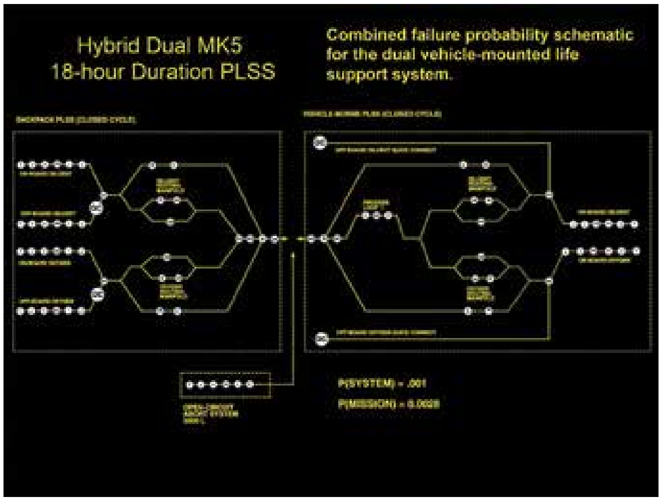

Figure 15. Fault-tree diagram of a dual rebreather system in which one rebreather is mounted on a propulsion vehicle and the second is backmounted.

Figure 16. First test of a vehicle-mounted rebreather at Wakulla Springs in 1998. Left to right: John Vanderleest, Jason Mallinson, Matt Matthes, and Andrew Poole. Inset: Rich Hudson.

During the mid-1990s I came up with the idea of vehicle-mounting an Mk5 (Figures 15, 16, 17). Given that we had Mk5 parts around, we conducted an experiment in which we mounted an Mk5 core on the bottom of a diver propulsion vehicle (DPV) and had a normal Mk5 backpack with dual gas supplies as the bailout system (Figure 16). The critical design issue when you do this is the breathing center of gravity of the counterlungs. You cannot mount them on the vehicle because the work of breathing in the most common diving attitudes is very uncomfortable. So we kept the over-the-shoulder counterlung design that we pioneered in the early Cis-Lunar rigs and created a dual counterlung (Figure 17). That left the question: How do you connect to the vehicle-mounted rebreather? To solve that problem we came up with inline breathing connectors that could be connected and disconnected while underwater — they were self-sealing once disconnected (Figure 17). This gave the diver the option of ditching the DPV (and the life-support rig) if something failed on that part of the equipment and then aborting on the completely unused backmount rig.

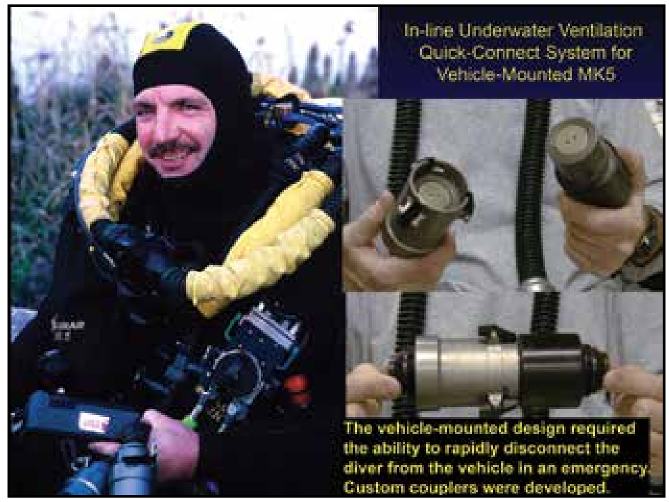

Figure 17. The vehicle-mounted dual rebreather still used over-the-shoulder counterlungs for both rigs, but separate long hoses with disconnects were needed to connect the counterlungs to the vehicle.

We tested it, and it worked. Figure 18 shows Andrew Poole driving it in Wakulla basin. The main problem, at least for cave diving, was this: Psychologically, in the minds of the divers, the issue now became "OK, I trust the life-support system, but what if that DPV dies? Now I lose the life-support redundancy, and I have to still carry a spare DPV." Transfer of the vehicle-mounted rebreather to another DPV while on a cave dive was considered a tedious affair. Perhaps with more time

Figure 18. First test dive of the vehicle-mounted rebreather system at Wakulla Springs, December 1998.

a quick-connect mounting system could have been developed, but at least as far as the Wakulla 2 project was concerned, no one wanted to risk losing the backup life-support system if the DPV died.

Before I leave this topic, I think vehicle-mounting of life support is a good idea. I think for scientific divers and others who are commuting to a fixed place to work, this would be a really elegant means of keeping things simple and freeing you up for detailed work at a fixed location. You commute to where you are going to work, you park the vehicle and its integral life-support rig and then go about your work. When you are ready, you commute back using the vehicle-mounted rebreather, leaving the backmount rig for bailout. This is analogous to thinking that has been going on in the space program for lunar- and Mars-related remote EVAs (in those scenarios they are looking at pressurized rovers for transit to a work site and standard spacesuits for local work). For underwater use it is imperative that the rebreather be left in a full-loop state and that all elements of the loop, including the mouthpiece and the quick-connect hoses, be completely leak free (otherwise you return to a useless, flooded piece of kit).

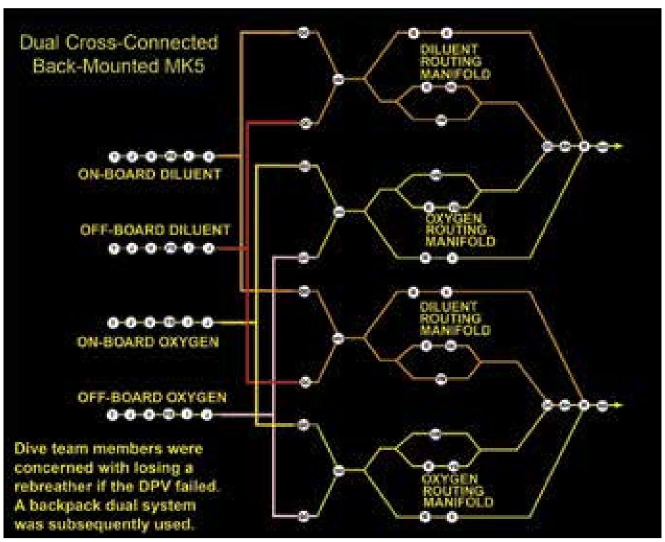

Figure 19. Fault-tree diagram for a simplified backmounted dual rebreather.

With that preamble, in the middle of the Wakulla 2 project we went back and said we should revisit the Cis-Lunar Mark 1 architecture but using Mk5 components and come up with something that is functional and survivable. Figure 19 shows the simplified dual-rebreather architecture we developed. We maintained dual gas supplies, and they could be rerouted between the two rebreathers. Figures 20 and 21 show Matt Matthes and Brian Kakuk preparing this rig for diving. Figure 22 shows Brian departing on one of the later survey missions at Wakulla using the rig. The dual rig had 18 hours of depth-independent life support, and he was carrying two 20-km

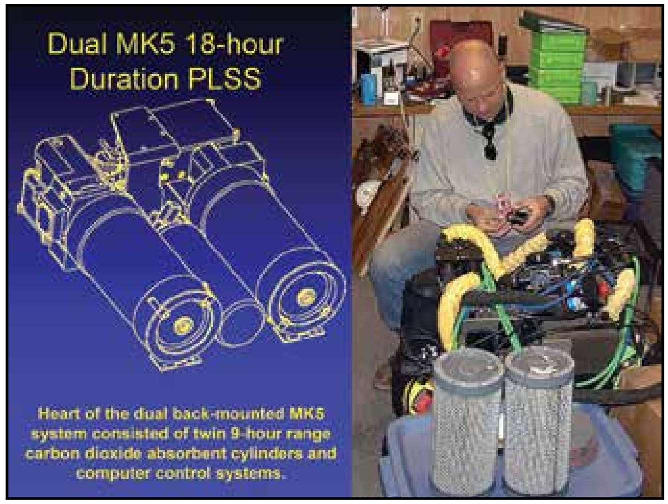

Figure 20. Assembly of the dual backmounted rebreather. The device used two radial hydrophobic carbon-dioxide absorbent canisters.

Figure 21. Final kitting up with the dual backmounted rebreather, January 1999. The small green tank is offboard oxygen; the small yellow tank is drysuit inflation argon supply. A second oxygen tank was placed inside the shell between the two CO_2 canisters.

Figure 22. Brian Kakuk begins a mapping dive in late January 1999 at Wakulla Springs with two long-range propulsion vehicles and the dual Mk5 backpack.

(12.4-mi)-range DPVs that were specially developed for the project. The word that most people who saw the rig used to characterize it was “intimidating” (in that, there was a lot to deal with in terms of task management on a cave dive when using that rig).

Figure 23. Rick Stanton and initial tests of the dual Mk5 backpack.

Figure 23 shows a photo of Rick Stanton (UK) and a back view of the first test configuration for the dual Mk5 rig. Rick is one of the world’s premier all-around divers. He is not only a diver but an excellent expeditionary caver as well. He is the kind of person who can take a tire inner tube and a couple of radiator hoses and a few other things and over a weekend come up with a rebreather in his garage. He can also strap on something like what is shown in Figure 23 and feel totally comfortable. Importantly, he is the kind of person who always returns from a technical dive. What makes him different? It is the fact that Rick has learned a level of discipline that is able to deal with every facet of the technical-diving environment and the hardware needed to work there. And he knows when to call a dive when things are not going well. He is situationally aware. People who do not have that discipline and that awareness are the ones who wind up on the statistics lists.

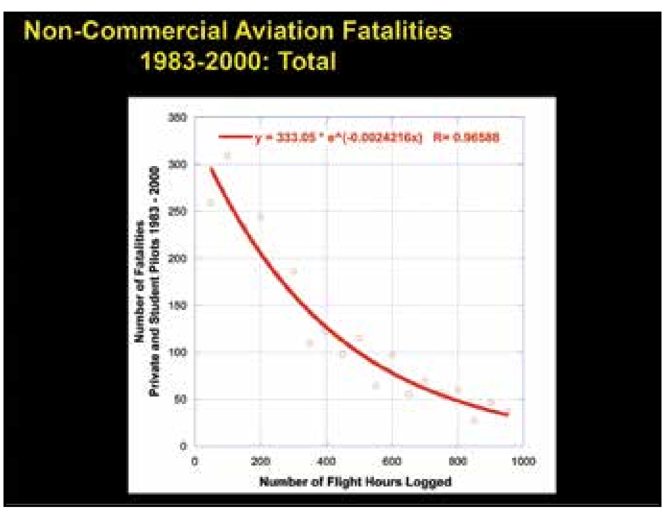

Figure 24. Chart showing pilot fatalities as a function of flight hours logged.

Let me now discuss some alternate statistics from analog environments. Figure 24 shows a plot of non-commercial-aviation pilot fatalities compiled by the Federal Aviation Administration (FAA) over a 20-year period. What you see is an exponential decrease in fatalities with experience. To me, that is not surprising.

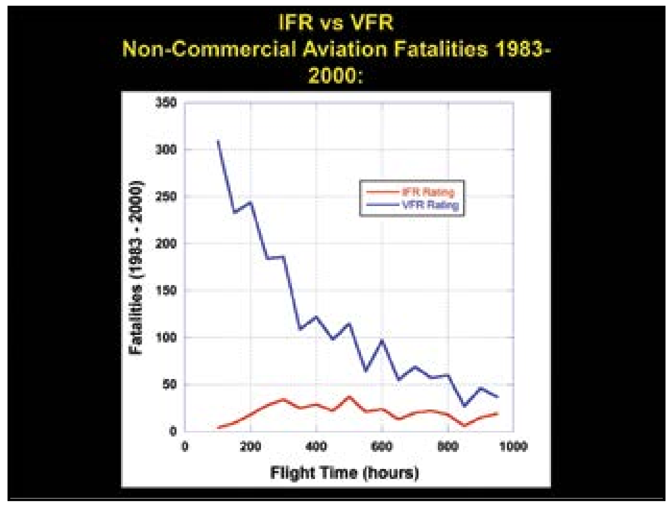

Figure 25. Chart showing IFR and VFR pilot fatalities versus flight hours logged.

But what is instructive is the further classification of those fatalities shown in Figure 25. IFR means instrument flight rules. VFR is visual flight rules. VFR is what you learn first — it means simply looking out the window to see what’s going on, and it requires good visibility. IFR means you are “instrument rated” so that you can fly in bad weather and in zero visibility. To obtain an IFR rating you need to be very comfortable with looking at instruments and using those, not the visual feedback, to drive your plane. Flying under such conditions is not dissimilar from the task-loading characteristics that you find on a tech dive.

So it is not surprising that you find significantly reduced fatality ratings for IFR pilots in general. For the sake of analogy one can classify IFR pilots as “disciplined.” There are a lot more pilots than there are rebreather divers today. I believe a similar curve could be constructed for divers. After a certain number of hours of experience, survivability rates converge (the VFR pilots are learning discipline). After that other issues come into play: environmental issues and things that you cannot necessarily control (e.g., an underwater sand slide that blocks a cave entrance). If you go into an old wreck your minor disturbance of simply passing through a corridor may trigger a random sequence of events.

Sometimes people have intuition telling them to back off, and sometimes you just get lucky (or unlucky). I heard of an incident where a couple of people a few years ago were caving in Alabama. They were at a well-known vertical cave training site. It was raining outside, so they were all waiting for their friends to climb the rope up the 80 m (262 ft) entrance shaft. There were two people sitting under a very large rock that I personally have sat under. It just so happened that day that the rain came down the wall and loosened the soil just enough so at just that time the rock decided to roll over. Simple probability was what played that card. The cave was popular enough and the number of touring cavers large enough that one day, statistically, that rock was going to roll over, and the probability was not zero that a person might be sitting under it. In the diving world, many still remember the tragedy of Parker Turner and Bill Gavin at Indian Springs. Sometimes even having the right stuff does not get you home.

So where we are right now with rebreather diving? Is it inherently dangerous (and if so, what can we do about it), or are we simply seeing the result of an increase in the number of rebreather divers? These are pertinent questions, because over the next decade we are going to see rebreathers gradually replacing traditional scuba. If so, then we can expect to see thousands of new rebreather divers each year. The problem of turning around the rebreather fatality curve is very similar in my mind to what was happening in the late 1960s and mid- to late-1970s in the cave-diving world. Figure 26 shows that there were an appalling number of people dying in Florida springs during that period. Open-water divers flocked to northern Florida and its beautiful, clear springs. And they went in and did not come out. There was an analogous discussion going on trying to figure out what to do about this back then. Of those 450 fatalities represented in Figure 26, more than half were recovered by one individual. After a while he began to notice recurrent trends. He wrote a little book about it. If you have not read *Basic Cave Diving: A Blueprint for Survival*, you should. There is an enormous amount of wisdom in those few pages. Sheck Exley was a humble person, a man of few but important words. His short book presented 10 rules.

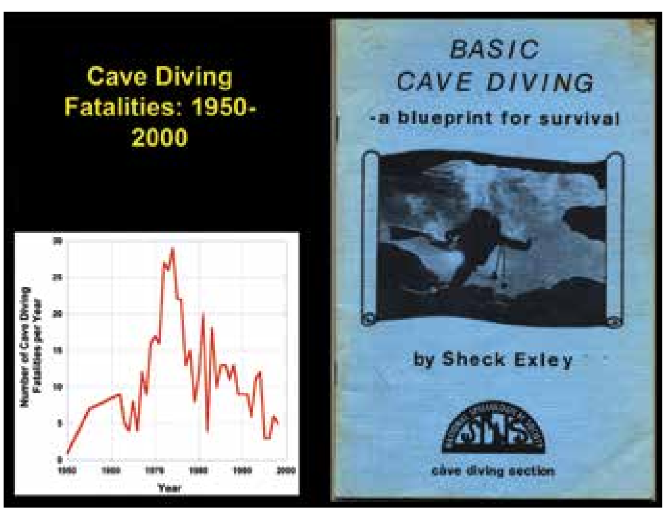

Figure 26. Cave-diving fatalities in the United States between 1950 and 2000 and the book introduced by Sheck Exley in the late 1970s that caused the precipitous drop shown in the plot.

Many of the rules seem like common sense (and apply equally to cave diving and rebreather diving): Avoid panic; use trustworthy gear; do not stir up silt; rehearse emergency procedures; carry equipment for emergency procedures; control overconfidence; do not violate the rules.

A lot of people in the rebreather world have translated the essence of this into the rebreather safety mantra "use your checklist." There is nothing wrong with that. But there is more to it. Here we are on the verge of an explosion (or an evolution, depending on your point of view) of new, recreational rebreather divers (e.g., Figure 27). Most of these people will not have the discipline of a Rick Stanton.

Figure 27. The number of recreational rebreather divers will eclipse tech divers within this decade. What do we need to do to keep them alive?

What are we going to do about that? Well, one thing that we can do is remove all but the simplest interactions with the rig as required learning. Cockpit designers learned early on that humans make very poor monitors. Simplifying interactions is part of architectural design. That is where the hardware and software engineers and human factors psychologists come in. The problem we face is how to outsmart the human creature — who is by nature fallible under pressure — by using silicon intelligence, something that is not subject to panic under stress. There are many ways of describing this type of human-machine interface wherein the human is presented with a very limited number of proactive options they can perform while the computer limits the extent of the ramifications of those actions to those calculated to not fall into a zone of potential (dive) system failure. I prefer the term "dive by wire" (Figure 28).

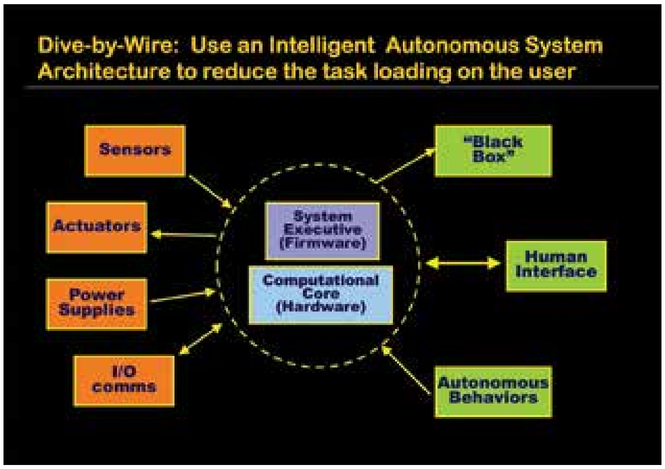

Figure 28. Block architectural chart for a "dive-by-wire" rebreather.

What we are discussing in Figure 28 is an intelligent system. There is a difference between an intelligent system and simply an automated system. Both make use of sensors, actuators, power supplies, communications systems, and both reside on computational hardware that has some form of underlying firmware and higher-level software to make the device work. Both will frequently have some form of human interface, and many life-critical systems will have some form of a black box (the term "flight recorder" is used in the aviation industry). To be a truly intelligent system, however, you have to go beyond scripted missions to ones controlled by autonomous behaviors.

Those who have seen videos of the Spirit, Opportunity, and Curiosity rovers on Mars may be tempted to believe those are autonomous vehicles. The reality is that for every mini mission in which the rover moves from one place to another, there is a team of programmers at Jet Propulsion Laboratories that has spent days analyzing the previously acquired geographic data, and that team will program out and upload to the rover a scripted mission for the next set of moves. That is not autonomy. It is a (very) remotely controlled automated system. Autonomous behaviors — that respond to a variety of sensory inputs from the environment — sometimes have integrated learning systems, and which seek to achieve a particular objective state that is communicated to the master control and advisory system — are the part and parcel of intelligent systems. The sum purpose of these adaptive, learning routines is to predict what will come next and to use that information to protect the life of the user.

I spoke of a black box. A data recorder. Why is it important? It is important for the same reason they have these things on all planes. If you have a plane with 400 people go down, everybody wants to know why, not the least of which is me, because I might have to fly in that plane. The FAA and the people who manufacture that airplane all want to know what happened and why. But that is postaccident investigation. The better use for the black box is to provide learning data that will provide statistical input for the development of autonomous behaviors.

It is useful to perceive of sensors as the eyeballs of an intelligent system. A sensor is something that acquires data about your environment. If you cannot see, you are in trouble. Figure 29 (and related Figure 30) shows several gas sensors that may be used in rebreathers. On the left in Figure 29 is a CO_2 sensor; on

Figure 29. Typical sensors used in rebreathers: CO_2 sensors (left) and oxygen sensors (right). Do you trust their readings? How do you know?

the right is a typical galvanic oxygen sensor. CO_2 sensors have been around in diving longer than many people are aware of. We designed them into the Cis-Lunar Mk2 in 1989. There are newer, more reliable CO_2 and O_2 sensors coming. Reliability and user safety in rebreathers begins with the ability to absolutely know what you are breathing at any given instant. If I perform the calibration of an O_2 sensor at the surface and then I go diving and immediately drop from 25°C (77°F) down to 2°C (36°F) up in the North Sea, how good is that data on oxygen partial pressure? For those who do not know the answer to that question, you should be very concerned. Oxygen sensors (and many other sensors) can be both temperature- and pressure-sensitive in ways that are not intuitive. When we consider true reliability for a rebreather we need to start here. There must be a mechanism to not only calibrate that sensor but also to continuously validate that sensor throughout the course of the dive. Sensors can drift and become unreliable for dozens of reasons. An adaptive (behavioral) algorithm is needed to determine how much we can trust a sensor and if that falls below an acceptable level, to advise, unequivocally, the user to abort the dive. This is true for all sensors in a rebreather, but particularly for the oxygen sensor since conditions can vary rapidly during a dive and the oxygen must remain in the green zone shown in Figure 30. To take that one step further, if you

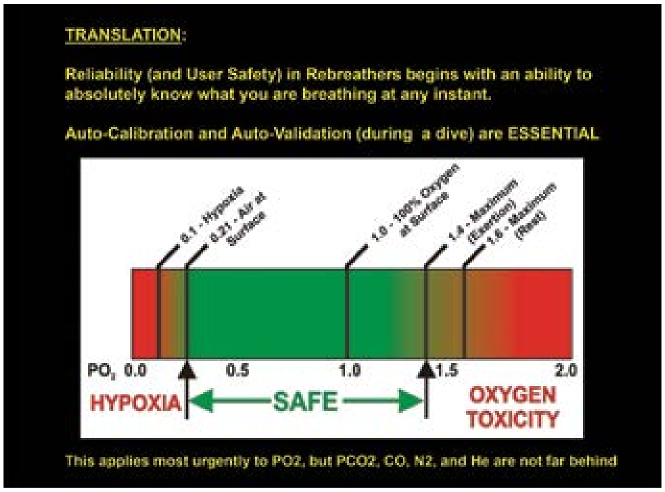

Figure 30. Rebreathers actively control the partial pressure of oxygen in the breathing loop, and it must be maintained in a survivable zone. Oxygen sensors provide the critical information to an onboard electronics system that controls PO_2. But sensors can age, change readings at different temperatures and pressures and can do so during the course of a dive. The only means to safely deal with that is to validate these sensors during the dive.

do not know for sure what your PO_2 is, then the control system (whether intelligent or automatic) is useless. Eventually we would like to sense and know the truth concerning the measurement of not only oxygen but also carbon dioxide, carbon monoxide, nitrogen, and helium.

The second key maxim for safe rebreather diving is that redundancy paths must exist for all critical subsystems, or a very clear and simple egress mechanism to a safe haven must exist (Figures 31 and 32). I note both cases here because the first one applies to tech divers and the latter applies to recreational divers. If I were to translate that, a true tech rig implies abort to closed-circuit. Let me state that one more time: A true tech rig implies abort to closed-circuit. Why? Because you still have an equal time constant for survival. If you abort to open-circuit, suddenly your time to resolve a problem underwater — particularly at depth — has just vanished.

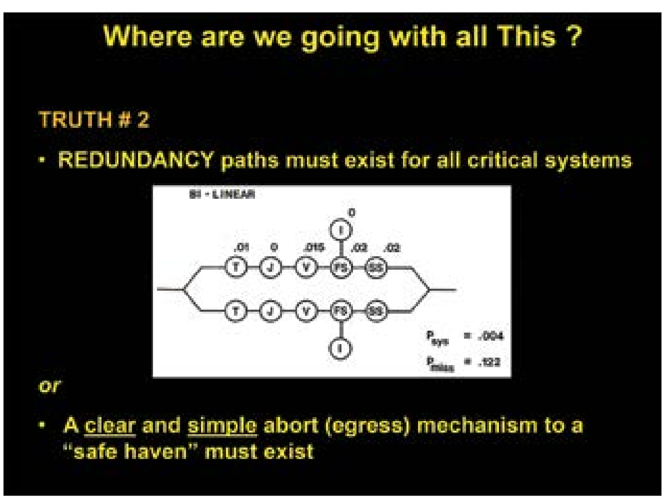

Figure 31. Two paths to survival: a) design redundant systems for situations where an abort-to-surface is not possible; b) design simple abort-to-surface mechanisms for no-decompression recreational diving.

Human factors design demands a reduction in the ways a person can interact with a system. How do you do that? There are many ways that you can approach this problem. Figure 33 shows a few possible examples: an unambiguous means of telling the diver it is time to leave; prepacked absorbent canisters to prevent CO_2 channeling; and your decompression history carried on the battery that powers the rig. The left-hand image in Figure 32 is a similar area for human factors design: having a heads-up display (HUD) on the mouthpiece with a very limited set of conditions that will activate it (thus fewer things to

Figure 32. Definitions for a true technical-diving rebreather and a recreational-diving rebreather.

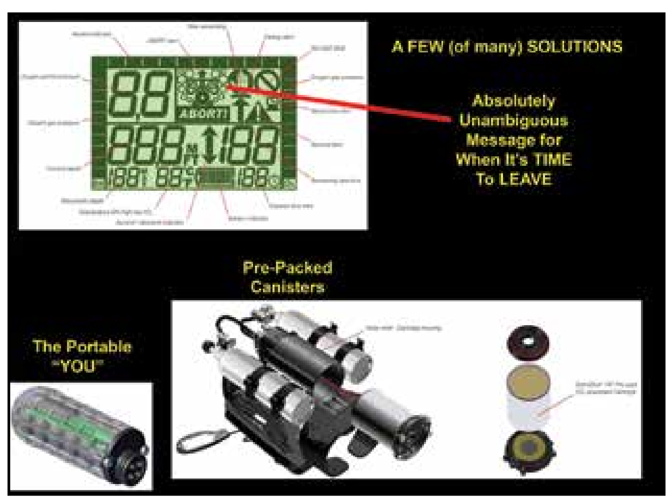

Figure 33. Three ways to reduce risk with rebreather design: a) have completely unambiguous instructions for a dive abort; b) use prepacked absorbent canisters; c) carry your decompression with you from rig to rig.

remember) and a simple one-motion lever that converts the mouthpiece from a closed-circuit rebreather (CCR) to a standard open-circuit regulator (for simple abort to the surface). Combine that with a system that tracks controlling resources and ensures that by aborting to open-circuit you can directly ascend to the surface (implying no-decompression diving) and you have several concepts for reducing task loading for a recreational rebreather diver.

There was a report issued by the British Health and Safety Executive (HSE) in 2011. I highly recommend this book to anyone who is a rebreather designer. It discusses hierarchical task analysis and human-error prediction. You can spend a lot of time doing analyses like this. I want to caution you that you do not want to go too far in the direction of believing that your simulation is absolute truth without a lot of physical validation through chamber and open-water test diving.

What these analyses will do, eventually, is guide you to the following generalized virtues of rebreather design:

- Keep the number of parts small so that the user has less to interact with.
- Where possible, force the user interaction (by design) to only proceed in a certain direction.
- Prevent single failures from drastically increasing the user's work load

Most tech rigs available today do not work this way — there are too many confusing options in the face of a task-loaded situation.

For the past few pages I have been arguing in favor of incorporating principles of intelligent system design into the control systems of rebreathers. This leaves open the important question: Can we really trust intelligent systems? These are, after all, life-support devices we are talking about.

I have had a privileged life as an engineer. I have been to a lot of interesting places and been involved with a lot of interesting projects, mostly at the request of the national labs. I cannot tell you everything I have done there, but I can tell you a couple of things that will bear on where we are today with regard to the reliability of intelligent systems.

Let us start the discussion with a few analog examples. Most people would consider that an automobile at the hands of someone who is not skilled could be a very lethal weapon, not only capable of killing themselves but also other people at the same time. Would you trust a computer to drive your car? If I were to have asked that question even a year or two ago, everybody would say, "You are crazy" or "That is science fiction, not reality."

But let us discuss what has been done in this area. Back in 1998 we took a Humvee (a four-wheel-drive military jeep on steroids) and converted it to run on intelligent onboard control. It was using primarily machine vision as its guidance, and there were several real-time control algorithms — behaviors — each of them simplistic in origin, yet combined they allowed for a piece of machinery guided by silicon to perform some rather impressive on- and off-road driving. The back of the Humvee was absolutely packed with computers. The whole idea was to drive like a bat out of hell, with no human at the wheel, but make sure that it could stop in any unusual situation. Figure 34 shows what the computer is thinking in a common driving scenario. It is guessing, in green colored lines based on machine vision, where the edges of the road are, and the blue lines represent the real-time calculated safe zone for operation of the vehicle. It was going 100 km (60 mi) per hour in Figure 34. There was a safety officer sitting in the vehicle with a red button to kill the program and take over if the computer made an incorrect decision.

Figure 34. An illustration of machine vision serving as the "eyes" for an intelligent system (in this case, an unmanned ground vehicle).

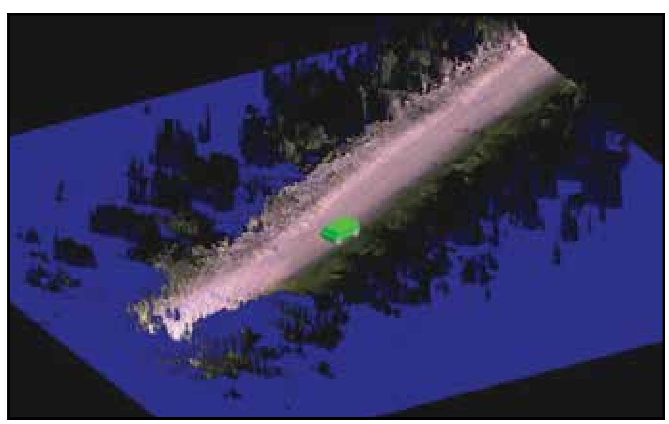

Figure 35. Composite computer-generated model of fused machine vision and LADAR 3D geometry for an unmanned ground vehicle on a dirt road in the woods.

That was 1998. Within five years we had integrated real-time laser radar (LADAR). Figure 35 shows a data replay frame of an unmanned driving mission in an unstructured environment — a dirt road in a forest — with a computer model of the vehicle shown in bright green. Figure 36 shows the actual vehicle, and by this time there was no place for a driver onboard. It is important to explain here that the only "instructions" given to the vehicle were its starting waypoint and the desired place where we wanted the vehicle to go (both as GPS points). What happened between those two points (the distance between which was measured in kilometers) was up to the vehicle.

Figure 36. Image of a fully unmanned ground vehicle self-navigating through a forest.

In 2007 Defense Advanced Research Projects Agency (DARPA) issued a challenge (with a significant prize) to whoever could build a car to negotiate through an urban environment with nobody at the wheel. Figure 37 shows the winning vehicle, heavily festooned with sensors. This was the entrant from Red

Figure 37. An unmanned ground vehicle operating in a suburban street environment. The vehicle does everything a human driver would do and is less distracted.

Whittaker's team out of Carnegie Mellon University. Although Figure 37 is a still image, you can see that the vehicle is making a turn at a stop sign. It had to detect the stop sign, make the stop, decide which way to go to get to its ultimate objective, turn on a turn signal, and then make the turn.

Most of what went into that machine, besides gathering data and pushing actuators, is shown in Figure 38. At the core of this operations diagram are behaviors. You can imagine behaviors for "obstacle detection" (maintaining a map of things you might hit); "traffic light detection" (Is there a light? If so, what color is it?); "traffic sign detection" (Is there a sign present? If

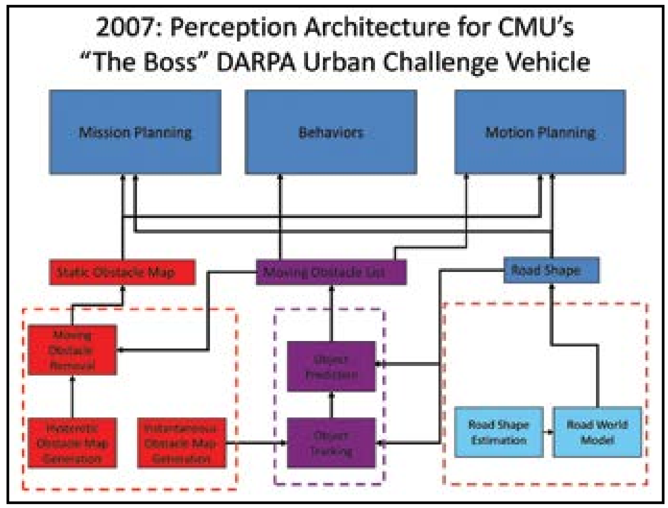

Figure 38. Perception architecture for an unmanned ground vehicle.

so, what type are we looking at?). The responses to those perceived situations are also behaviors. The above examples are simple and known to every driver. But how do you respond when confronted with unusual environments and situations? That is where a lot of work goes into creating decision-tree structures that drive behaviors. Think about how that might apply to diving. How would you break down every situation you have come across in diving? Well, you would start by describing a particular scenario and then describe what you would do in that situation. For example, suppose you have just encountered a deep unexplored shaft in a flooded cave; your response might be to check your consumables levels, check that all of your systems are working correctly, estimate how much time you have remaining before you need to leave, and then make a decision: descend or not. Many of those tasks just described could be considered fundamental (e.g., what is the state of your consumables) and could be running as a completely separate calculation in parallel with all the rest of the behaviors described. As you describe more and more of these you find that the decision tree is hierarchical — that is, it can be broken down from a simple category (e.g., I am exploring) to the more complex (Should I descend this shaft?).

Behaviors (state machines) are a means of distilling the essence of what a human would do (and more) into onboard code. In early 2012 the State of Nevada issued the first autonomous driver's license for Google's mapping cars (Figure 39). So you may say, "Well, those are just cars. What does that have to do with diving?"

Figure 39. Google's self-driving car, used to automatically create "street views" for Google Maps.

Figure 40. The DEPTHX underwater vehicle successor, known as ENDURANCE, preparing for a 10-hour subice mission in Antarctica. The vehicle can explore, map, and navigate on its own in 3D with only limited goal state programming.

Figure 40 shows the Deep Phreatic Thermal Explorer (DEPTHX) autonomous underwater vehicle. We used it to explore the Cenote Zacaton in northern Mexico (Figure 41). Like a human would, the vehicle built a map in its mind as it explored down into the cenote and deduced its own location within the map it just created (see Figure 42). It used that information to find its way home — the first vehicle to ever do so.

Figure 41. Cenote Zacaton in northern Mexico. This 140-m (459-ft) diameter hydrothermal spring was explored by DEPTHX in 2007 to a depth of 335 m (1,099 ft).

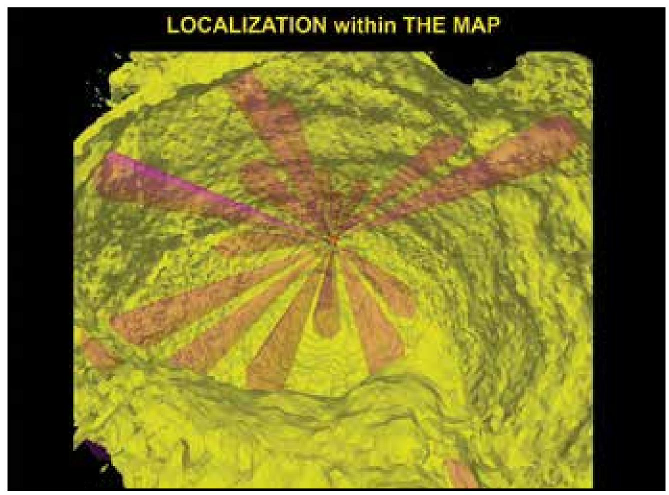

Figure 42. A data replay frame from a DEPTHX mission to Cenote Zacaton. The yellow faceted surface represents the map of Zacaton created by DEPTHX while exploring downward. The red beams represent tight beam sonar pings. The system uses these to estimate its current position within the map.

Figure 43 shows a profile view of Cenote Zacaton, created by DEPTHX. The software architecture for the vehicle is shown in Figure 44. Some of these modules are automated procedures (e.g., Navigator, Telemetry Manager, Thrust Controller) that accept fixed inputs and have fixed outputs. Others are complex state machine hierarchies (e.g., health monitor, mission planner, goal manager, science manager) that seek to achieve more global objectives when given a flood of sensed data about the environment and the vehicle. It is instructive to point out that the map shown in Figure 43 was produced with only a handful of guidelines given to the vehicle as "goals," which included such objectives and limitations as "explore"; "do not exceed a depth of 500 m (1,640 ft)"; "do not get any closer than 20 m (66 ft) from any obstacle"; and "if any critical consumable is less than 67 percent full, return home." You can tell that cave divers had input for the last criteria. The behavior modules

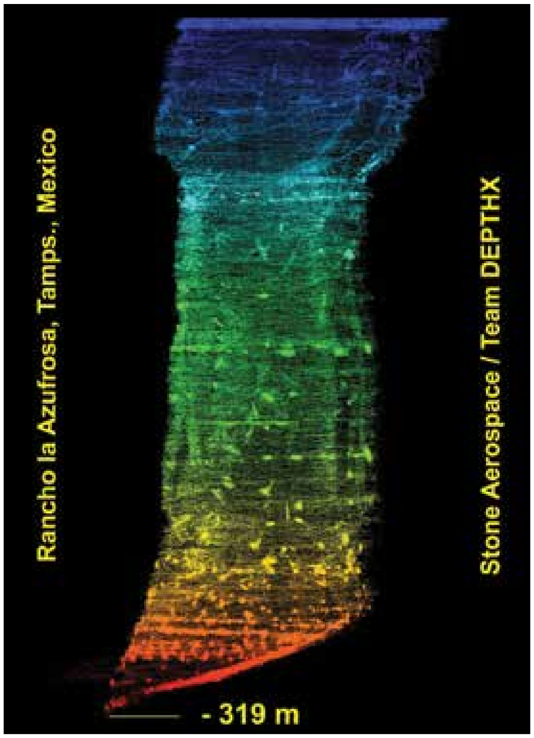

Figure 43 (version v2). Profile map of Cenote Zacaton created by DEPTHX. Green points above the water surface (blue) are from surface-based 3D LADAR data. Bottom breakdown pile slope is in red, and the image is looking into the narrow (90 m [295 ft] wide) view; the long axis (into the page) width is 140 m (459 ft). Total depth of the geological feature is 335 m (1,099 ft).

took care of all the rest. The vehicle was designed to be redundant and could lose half of its thrusters and power supplies and still return home — again thinking like a cave diver.

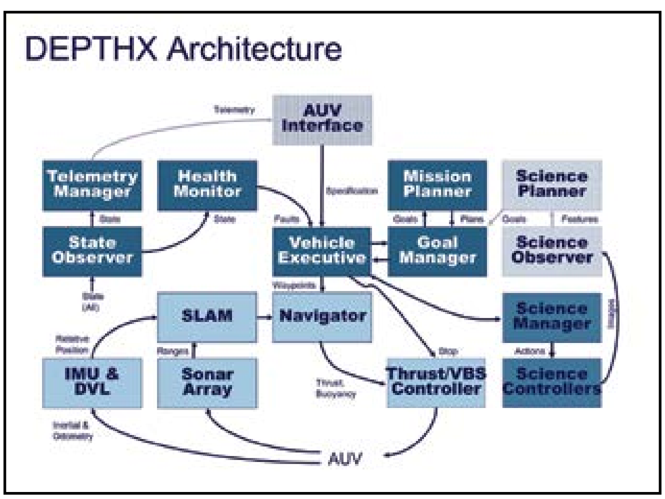

Figure 44. Computational architecture for the DEPTHX vehicle. This represents a mix of fixed I/O automated modules (e.g., Navigator) that accept fixed inputs and produce a numeric output, and a series of behavioral modules that interact to achieve a simple, higher level goal (most of the modules on the right side of this diagram are behavior based).

Does behavioral programming work? The most complex mission undertaken by DEPTHX was the search for microbiological life. The task hierarchy (shown in Figures 45 through 48) included:

- Explore.
- Map (in 3D).
- Measure water chemistry (in 3D).
- Calculate the location of chemistry gradients and shock layers (in 3D).
- Follow the gradient to a wall surface.
- Follow the wall (along the gradient intersection), and look for pronounced changes in background coloration (which are an indicator of microbial communities (e.g., sulphur-eating bacteria that thrive on a hydrogen-sulphide lens).

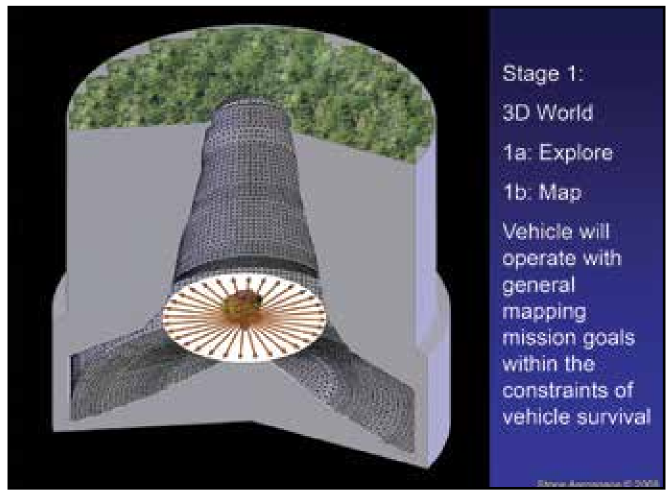

Figure 45. The first two stages of the DEPTHX life-discovery top-level behavior: "Explore" (Task 1a) and "Map" (Task 1b). These are the first two things a human would do upon entering unknown territory.

Each of these was a complex behavior. In 2007 DEPTHX was programmed with these goal states and nothing else. It descended to the 300-m (984-ft) level of Zacaton, found a zone of hydrogen sulphide and followed it to the wall, where it found a promising site and collected a rock core sample along with several liters of the surrounding water. That sample, and others similarly collected, were later shown to contain four new phyla of bacteria, at a time when fewer than 100 were known to exist on Earth.

The question to ask at this point is: What does this have to do with diving and rebreathers? The answer is: A lot. We can, in fact, build an autonomous, self-diagnosing rebreather. This is not speculation. For those who have not seen a demonstration of the Poseidon Mk VI recreational rebreather, I would recommend doing so. The Mk VI has a fully automated predive. What previously was a tedious, time-consuming multipage check-list-driven event now takes about three minutes and requires interaction from the diver only in three places (two of which

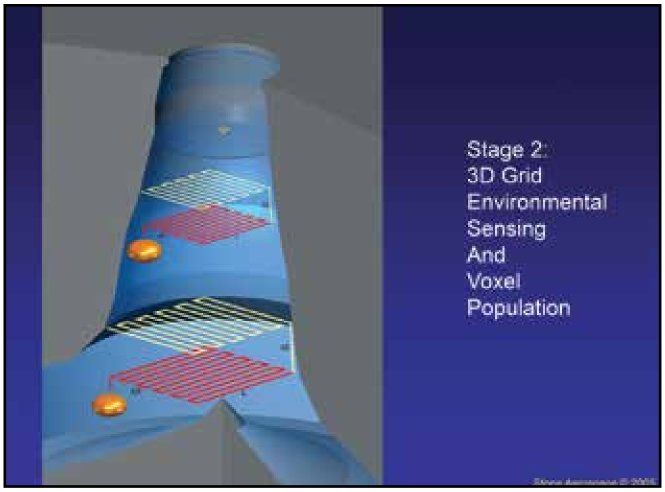

Figure 46. The second stage of the DEPTHX life-discovery behavior. "Scan through space, and map the 3D chemistry of the world." Place the chemistry and environmental data into 3D "voxels"… imaginary cubes of the world diced to arbitrary scale — for DEPTHX the cube size was 1 m (3 ft).

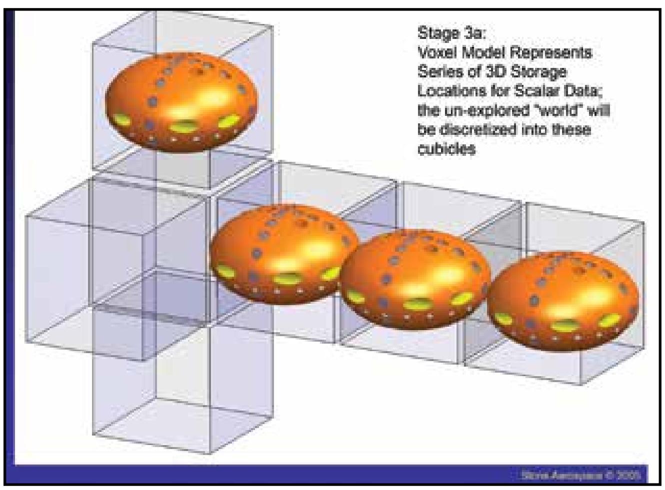

Figure 47. Graphical depiction of how DEPTHX discretized the physical world into digital voxels.

involve switching the open-/closed-circuit mouthpiece state and one of which involves doing a prebreathe while the system monitors the loop response). The automation of predive takes away some of the perceived disadvantages to rebreather divers when working in mixed company with open-circuit divers (who are usually ready to get into the water faster). The use of similar automated and behavior-based sensing and decision-making processes can be successively applied to other scenarios that arise in rebreather diving. I believe we will begin to see this type of approach incorporated throughout rebreather control systems in the next few years. The improvement in diving safety as a result of this should be significant. It will supplement, and exceed, the ability of a diver to diagnose situations before they become critical. Ideally, the advice then given to the diver will be simple and direct (e.g., abort on OC to the surface now).

That leaves us with a couple of remaining issues regarding rebreather training and diving practice. From an instructor's standpoint I would like to know: Is there a way that we can test whether a diver, particularly a recreational diver candidate, has enough discipline to be diving a rebreather? And can we compensate through engineering such that most people can

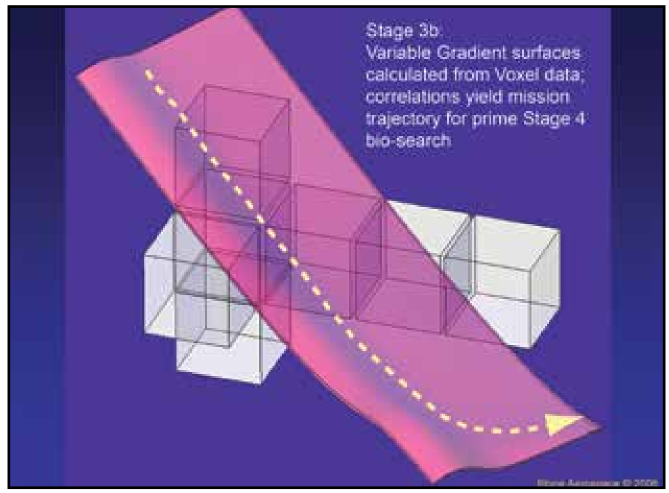

Figure 48. Stage 3 of the DEPTHX life-discovery behavior: (Task 3a) Determine if gradients or shock layers exist in the environmental data (e.g., chemoclines, haloclines, thermoclines); and (Task 3b) follow that gradient to a wall surface (because microbes like to live on surfaces near chemical gradients.

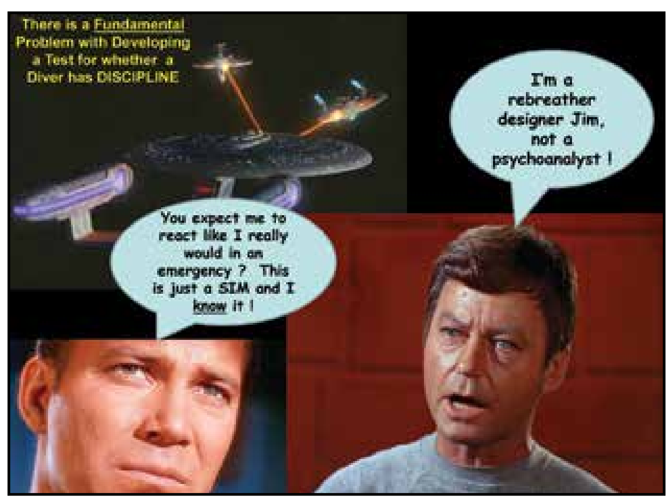

Figure 49. As graphically depicted in several Star Trek *episodes and movies, Captain Kirk famously defeats the Kobayashi Maru stress test (by either knowing the test is a simulation and therefore acting differently than he would if actually in the situation for real, or by changing the test by secretly rewriting the test program). Developing a test to determine if rebreather trainee candidates have the "right stuff" (discipline) to be a safe rebreather diver is one of the fundamental hurdles the diving industry must confront.*

enjoy recreational rebreather diving? There is a fundamental dilemma here. If you know you are being tested, then you have a different mindset than if you are not being tested (Figure 49). As a rebreather designer, I have a problem here because I am not a psychoanalyst. We need a way to quantitatively characterize the response of an individual under controlled conditions that will presage their response when under actual or perceived threat underwater. We do not want to first discover that a person is prone to panic when they are 40 m (130 ft) underwater. We would like to have them go through a realistic simulation and, based on the results, be able to say politely, "Friend, you really ought not to be a rebreather diver. And, by the way, I am not going to sell you a rig." To my knowledge no one in the diving (or aerospace) community has come up with such a test — but we need one.

I would like to finish with a discussion of ways that we can help rebreather divers be better divers. Probably the most important potential training aid that can be carried on a rebreather is a black box (a data recorder). Not only is it essential for rebreather developers to have this data (to see if the device is operating properly over a wide range of diving conditions), but divers can have a remote agent (think Internet application) analyze their dive logs and point out mistakes they have been making in how they operate the rig and manage their dives. Think of it as a remote expert system, like having a personal coach. We have had onboard data-logging systems on Cis-Lunar rebreathers since 1987, so we have been at this game for a long time. The obvious data (e.g., see Figures 50, 51, 52) includes depth, gas partial pressures, and tank pressures versus time. You can also produce derivative quantities such as the rate for oxygen consumption (VO_2; Figure 53). There are many, many other things you can diagnose, and there are many "health" diagnostics and "error" states that can be logged. All of these are incredibly useful to demonstrating and predicting diver behavior.

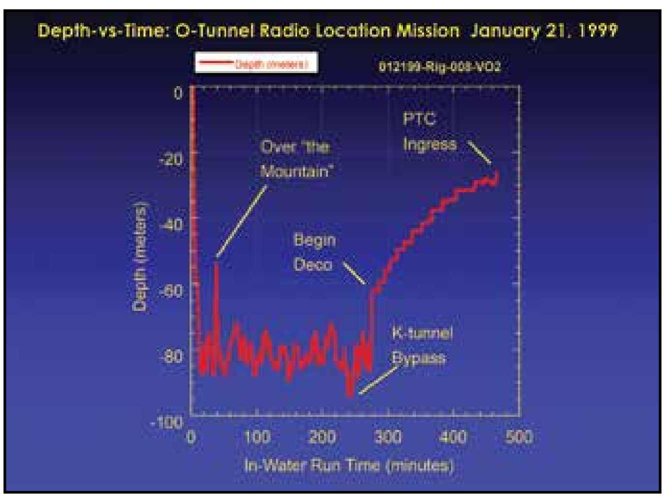

Figure 50. Typical base-level stored data from the Mk5 rebreather: depth versus time.

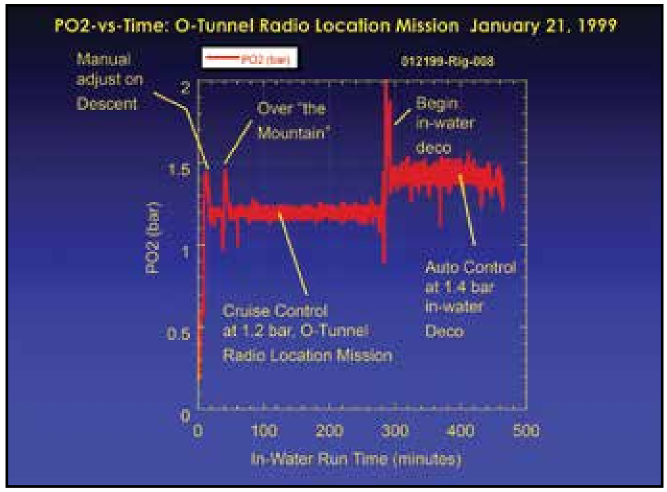

Figure 51. Typical base-level stored data from the Mk5 rebreather: PO_2 versus time.

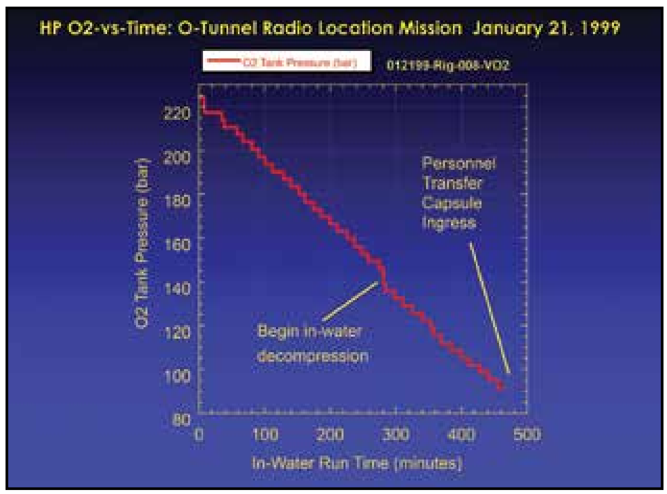

Figure 52. Typical base-level stored data from the Mk5 rebreather: oxygen tank pressure versus time.

In 1999 we were logging about 670 events per hour with the Cis-Lunar Mk5. Today it is about 25,000 events per hour with the Poseidon Mk6. There is a lot of good information in there. Let me give you one example of why having a black box is useful. Early on when we were working on the Mk6, we were coming up against a complex behavioral problem in the control system. Figure 54 shows two oxygen sensor traces recorded by the Mk6 black box during a test dive performed by Rich Pyle. Every five minutes the rig validates the primary oxygen sensor. The primary sensor is seen in Figure 54 as gradually drifting (dropping) away from the secondary sensor PO_2. And we wondered for a long time what was going on until we started looking at this data carefully.

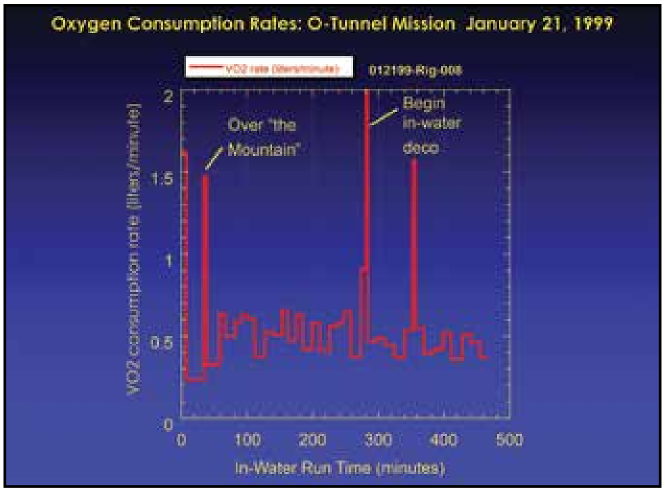

Figure 53. Typical derived data from the Mk5 rebreather: VO_2 (oxygen consumption rate) versus time.*

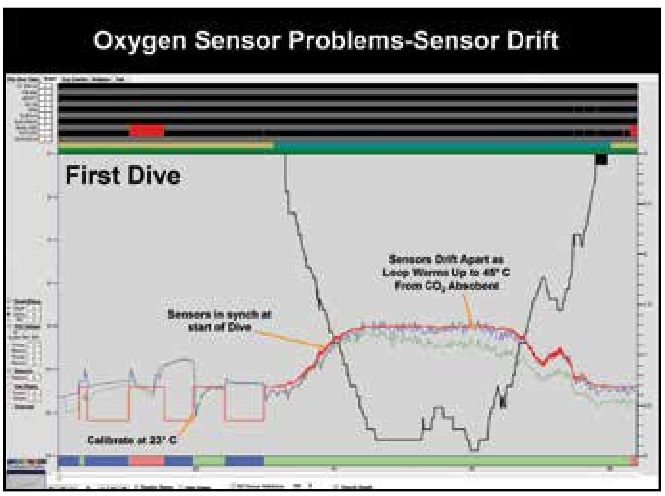

Figure 54. Divergence of oxygen sensor readings due to differential heating of the sensors as a result of CO_2 absorbent canister heating.

Pyle observed that he and his dive partner had started the predive calibration of their oxygen sensors at a surface temperature of 23ºC (73ºF). By the time they were moving underwater, the CO_2 absorbent began heating up and was changing the temperature constant on the oxygen sensors such that the primary and secondary PO_2 sensors were diverging. Pyle made the prescient suggestion to recalibrate the rigs while the canister was still hot to see if the effect was reversible (see Figure 55). They did so and found that the two sensors were now in lock step for the remainder of their dive. This underscored the absolute necessity of having precise temperature compensation for oxygen sensing. Had we not had detailed black box data for those sensors and a lot of supporting environmental data, the problem might have persisted.

But the utility of a black box goes beyond test-dive troubleshooting — by closing an information loop for the user. By

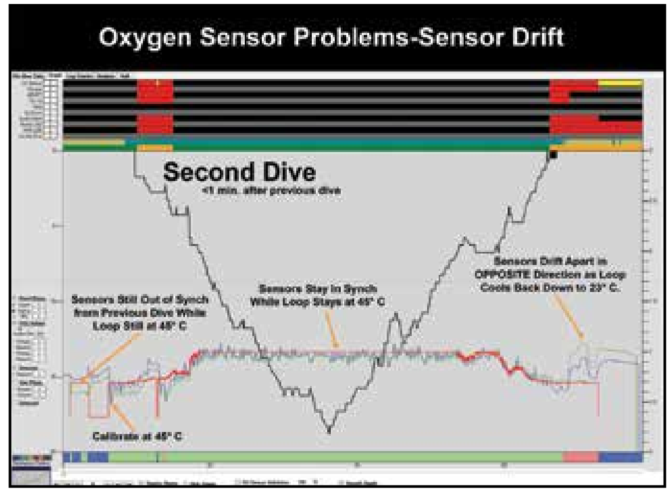

Figure 55. Recalibration of differentially heated oxygen sensors while the sensors are in use leads to stable lock, but the sensors drift apart when the dive is over (and the canister is no longer generating heat). Such behavior highlights the temperature sensitivity of the galvanic-style oxygen sensors that are used in every rebreather today. Dealing with this means tracking the precise temperature of each oxygen sensor and compensating for the temperature change in the reported PO_2.

interpreting personal dive data properly, a diver might come to realize that he has bad diving habits. By simply reviewing that data, you can say, "Hey, I need to change the way I do things in my diving." An even better implementation is for all rebreather divers to upload their black box data to a master archive that can be sifted for incidents and non-incidents and which can be processed to deduce whether a diver has bad habits and can discretely inform him of such (e.g., via a private email as a benefit of having uploaded the data). Such a master database is best implemented by a neutral public service organization such as DAN. This is the final missing link to dramatic reduction of fatalities in rebreather diving.

Let me close by addressing a related point that was brought up several times during the RF3 conference. There is not enough publicly available rebreather black box data for safety organizations to analyze the statistical trends and make recommendations for safer rebreather diving practices. There were several calls at RF3 to "do something" about this data gap. At the time of this writing, Poseidon has compiled a massive database on the Mk6 — largely contributed from thousands of dives logged by test divers and others who want to contribute their dive data with the idea that it will help others (and potentially themselves). In 2012 Poseidon signed an agreement with DAN to provide all of their rebreather dive-log data. Poseidon will also provide DAN access to fatal and near-miss dive logs, pending release by authorities and family.

Poseidon has additionally sought to encourage all Poseidon divers to provide ancillary (metadata) information that would quantify the nature of their dives. Was there a problem during a dive? Did anything else happen that would be of use to know how to improve safety? The hope is that this will become a viral phenomenon among rebreather divers, particularly the new generation of people who are accustomed to the Internet, Twitter, and Facebook. The benefit for contributing to the master database is that you get feedback on whether your rebreather diving practices are average, excellent, or in need of improvement. Our feeling is that open data is good data. It will serve to both improve manufacturing practices as well as lead to safer rebreather diving behavior. I implore all rebreather manufacturers to do the same.

PUBLIC DISCUSSION

UNIDENTIFIED SPEAKER: My background is in aviation. Can the diving industry support the cost involved in developing this technology to make this a viable business model? There is a lot of investment that has to be recouped. As more manufacturers get there, the market share goes down.

BILL STONE: Right now there is a wealth of talent in autonomous systems. So if you want that capability, place an ad. You will be surprised who responds. During the past few years Google has been snatching the world's supply of really talented robotics people for their intelligent-car project. As that project is coming to a conclusion, they have been spinning those people off. It is not an unbearable burden to take what you have and add instructor behavior. I am not going to tell you how to do it, but I will say it is not an insurmountable hurdle.

MARK CANEY: I congratulate you on the intention to provide all that data — in particular because it is going to give us an indication of when dives are going right as well as when they go wrong so that we have a much clearer picture of where the problems are. A difference between now and RF2 is that we have more clearly identified a recreational rebreather diver. When it comes to analyzing this data, I hope that we can clarify which dives are technical sector and which are recreational so we get a clear picture of the risks and what is needed to improve safety. I am very interested to see the effects of the human-machine interface that Dr. Fock spoke about.

BILL STONE: For a general rebreather database to work, we need to convince the diving community it is worthwhile. Younger divers need to believe it is cool to get on Facebook, annotate their dives, and send them in. While it is purely voluntary, you ought to do this if you want to be a good diver. It is not only going to help you, it is going to help the community. By taking 20 seconds to click off a few boxes that say "the dive was perfectly great, no problems" or "I ran out of gas" or "My electronics crashed" would be extraordinarily useful. If they want to put more in, there would be a place for it. We cannot do it without them. We cannot give you data unless the divers think it is cool to take a minute or two to annotate and upload the data. It benefits everyone. The more data there are, the better the ability to statistically isolate a problem. Once you leave your course you do not have the benefit of an instructor standing over your shoulder advising you of a mistake. It takes time to be disciplined. You have a job, you have all your daily time pressures. You get out to the dive site late, and all you want to do is go diving. Maybe you just cut a few corners. The only reason that tech divers in this room who have been here for any length of time are still here is because they do not do that. They know the consequences. They have a checklist in their back pocket, and they use it every time, every dive. So to me the big thing that can happen with the training agencies to really kickstart this whole idea is to start informing new divers. Get the following message into a student's mind as early as possible: "If you are a serious diver, then upload." That is the message.

TOWARD A NEW ERA IN RECREATIONAL AND TECHNICAL REBREATHER DIVING

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ABSTRACT

Modern non-commercial civilian diving using closed-circuit rebreathers emerged approximately two decades ago amid the "technical"-diving revolution and, more recently, has begun to appear within the realm of recreational diving. Although information on relevant diving physiology and general rebreather design accumulated by commercial- and military-diving communities guided the use of rebreather technology for civilian technical and recreational divers, major aspects of training, diving procedures and protocols, and more specific rebreather design needed to be reinvented and optimized for the particular sorts of diving regimes encountered by technical and recreational divers. While early developments in this new emerging community of divers necessarily required substantial trial and error and relied upon opinions and recommendations from individual rebreather users (based largely on anecdote and personal experience), the community and associated industry have now matured to the point where a more objective metric is called for. I outline several aspects of how rebreather divers, developers, manufacturers, and training agencies can coordinate efforts to gather, share, and make available for analysis robust, objective data concerning both the habits and patterns of practice related to rebreather divers, as well as detailed data recorded during actual rebreather dives. This will require close coordination between leaders of the rebreather-diving community (including manufacturers as well as the divers themselves), the Rebreather Education and Safety Association (RESA), and Divers Alert Network (DAN). The data-gathering paradigm should be modeled after DAN's Project Dive Exploration (PDE), and a new social standard for contributing and sharing data among both rebreather manufacturers and individual divers should be fostered.

Keywords: data, DAN, database, dive log, PDE

INTRODUCTION

I wear a number of different hats. The hat that most readers of this article are likely to associate with me is the one I have worn as an early adopter of technical-diving practices and particularly as a rebreather diver and designer. I began using the Cis-Lunar MK-4 rebreather in 1994; along with Bill Stone, Nigel Jones and others, I was part of a team that developed subsequent generations of Cis-Lunar rebreathers, including the Mk-5P and the Poseidon MK-6 Discovery. Another hat that many in the diving community associate with me is the one I wear as an ichthyologist (a marine biologist who studies fishes). Indeed, it has been my life-long passion for exploring coral reefs in search of new species of fishes that both drew me to and keeps me engaged in the advanced- and technical-diving communities.

But many in this community might not be familiar with another hat that I wear. In fact, this hat is the one that has dominated my professional career for more than a quarter of a century and represents my primary job description at Bishop Museum in Honolulu, where I have worked since 1986. Wearing this hat, I am a designer, developer, programmer, implementer, and maintainer of computer database management systems. Specifically, the database systems I create are designed to manage information related to biodiversity. This includes database systems for natural history specimens as well as international databases related to scientific names of organisms and associated scientific literature. As a commissioner for the International Commission on Zoological Nomenclature (ICZN), my primary role in recent years has been the development of ZooBank — the official online registry of scientific names of animals. My involvement in this field includes an active role in the establishment of international standards for biodiversity data. In other words, as much as I consider myself a rebreather nerd and a fish nerd, I am in fact even more so a database nerd.

It should come as no surprise that just as my involvement with rebreathers overlaps with my passion for fishes (in the form of exploring deep coral reefs), and my research on new species and geographic distributions of fishes overlaps with my career as a database developer (through my involvement with biodiversity informatics standards and development), so too my diver's hat and my database developer's hat converge. In fact, the association between these two aspects of my life has been the most long-standing of the three. The very first database management system I created — back in 1980 on my father's Apple II+ computer — was a dive log system that allowed me to document my very earliest scuba dives.

Figure 1. Centropyge boylei *from the Cook Islands at 300 ft (91 m). Photo by Richard L. Pyle.*

The main message of this article, therefore, is not about my thoughts concerning rebreather diving techniques or systems design, nor is it about how I have used rebreather technology to access previously unexplored coral reefs in remote tropical locations. Instead, this article is focused on what I believe is the dawn of the next major era in recreational and technical rebreather diving: the rebreather data revolution.

THE EMERGENCE OF A NEW DIVING COMMUNITY

In the early days of civilian, non-commercial rebreather diving, the information available about closed-circuit rebreather operations was incomplete. Although the military had been using rebreathers for many years, and the commercial-diving world had some experience with rebreather technology (not all of it good), the knowledge and insights from these groups had limited practical value to the fledgling technical-diving community. Certainly, wisdom about diving physiology (particularly in terms of decompression physiology and oxygen exposure) and experience concerning rebreather design (such as work of breathing and carbon-dioxide absorbent dynamics) shared by military- and commercial-diving personnel were extremely valuable to the new breed of rebreather-using technical and recreational divers. But in areas of training, dive protocol, and modern advancements in rebreather design, technical divers had little to go on. Most of the training that military divers undergo involves advanced underwater navigation, combat techniques, and other tasks that such divers must perform in the course of their work. To these highly skilled divers the rebreather is a tool that allows them to carry out a specific mission. In most cases, the person who prepares and maintains the rebreather in a military paradigm is not the same person who wears it underwater. In the commercial world, rebreathers had become largely relegated to backup for surface-supplied breathing-gas systems in saturation-diving situations. In both military- and commercial-diving operations, decompression techniques were optimized around situations with relatively robust logistical infrastructure, including underwater habitats and surface-based decompression (Sur-D) protocols. Rebreather design in these contexts emphasized things such as magnetic signature and work of breathing at extreme depths rather than integrated decompression calculations, sophisticated displays, and alarm systems.

Figure 2. A team of research divers with the University of Hawaii conduct an experiment on corals 280 ft (85 m) deep off Maui, while the university's Pisces submersible looks on. Photo by Richard L. Pyle.

By the time of the first Rebreather Forum in 1994, rebreather diving by non-commercial civilian divers (i.e., mostly technical divers) was still in its infancy. Thanks to the efforts of training agencies, a series of technical-diving conferences, online email lists and other forums for discussion, and particularly the Rebreather Forum 2.0 in 1996, the field of technical rebreather diving began to mature and entered its adolescent phase. Standards for diving practice began to emerge as the rebreather-diving community slowly started to grow. Electronic systems became more sophisticated, and rebreather developers began to refine their designs in response to the experiences of an ever-increasing base of end-users. Unfortunately, although a lot of progress has been made in the 16-year period leading up to the Rebreather Forum 3.0 (RF3) in 2012, the rebreather community in general continues to suffer from the growing pains of an industry enduring its "teenage" years.

We are now at the point in history where the primary market for rebreathers is about to shift from the technical-diving community to the recreational-diving community. As this begins to happen, the number of divers using rebreathers and the number of rebreather dives conducted are likely to increase dramatically. Unfortunately, recent estimations suggest that fatality rates among recreational and technical rebreather divers may be five to 10 times greater than for recreational scuba divers. As long as this continues to be true, it will represent a barrier to growth in the industry. As a community, we must get serious about addressing this discrepancy in risk between rebreather diving and scuba diving — to identify the causes and implement the solutions. The time has come to change the paradigm for how we approach rebreather design and rebreather-diving practices in the recreational- and technical-diving arena. In short, it is time that the rebreather community entered adulthood.

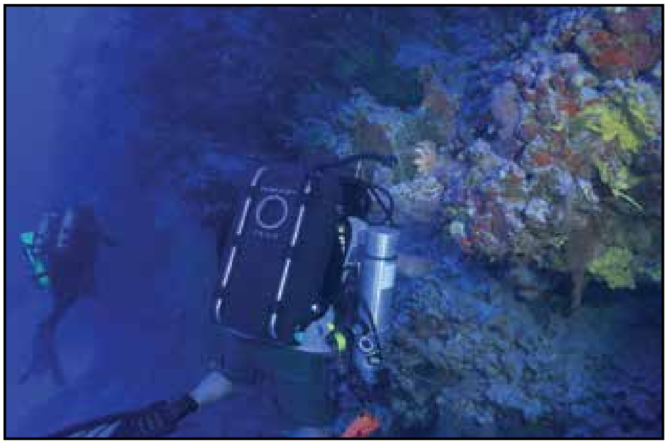

Figure 3. A team of research divers collect specimens at a depth of 361 ft (110 m) in Rarotonga. Photo by Robert K. Whitton.

A NEW ERA IN DATA-DRIVEN REBREATHER DIVING

As a group of passionate divers, and as a growing sector of the broader diving industry, the community of rebreather divers, designers, and manufacturers share a responsibility to embrace a new era for how we advance the field. The emphasis should no longer be about arm-waving diatribes espousing the virtues of one particular model or manufacturer, or disparaging another. It should not be about keeping information secret (for purposes of industrial paranoia or personal pride) unnecessarily. We should no longer rely on the opinions of experts and gurus (self-proclaimed or otherwise) or the collective anecdote of rebreather divers around the world shared via Internet forums as our only source of insight into improving rebreather safety. The time has come to establish a bold new industry standard among both manufacturers and divers that fosters the routine capture, sharing, and objective analysis of real-world data.

Below I outline a series of specific steps we can take to foster this new data-driven approach to rebreather diving. The overarching goal is to dramatically improve our understanding of what really causes diving accidents (particularly diving fatalities) involving rebreathers and how best to prevent such accidents in the future through the acquisition and sharing of data. This involves both the improved documentation of patterns of actual diving habits (i.e., how many divers, how many and what sorts of dives, details about diving environments and protocols) and the acquisition of detailed information about sensor readings, control actions, and other parameters recorded by the rebreather electronics during the dives themselves. If we, as a broader diving community, can come together to establish data standards and information infrastructures for capturing, sharing, and interpreting data in both of these areas, and (perhaps more important) to establish new social norms within our community, we will have a major positive impact in overall rebreather-diving safety and will improve the health and vitality of our hobby and our industry going forward.

Documenting the denominator

It is probably safe to assume that everyone understands the value of knowing how many rebreather-diving accidents have occurred. However, as important as this very fundamental piece of information is, the number of accidents alone tells us very little of actual value for evaluating rebreather-diving safety in general. For example, if we knew there were 10 fatal accidents involving rebreathers one year and 20 the following year, it might at first glance appear that the situation was getting worse. However, if 1,000 rebreather divers conducted a total of 10,000 dives the first year, and 10,000 rebreather divers conducted a total of 100,000 dives the following year, the situation is actually getting better. One fatal accident in 500 divers (or 5,000 dives) is considerably better than one fatal accident in 100 divers (or 1,000 dives). The trouble is, it is extremely difficult to document (or even estimate) the denominator in diving because there is no widely adopted or standardized mechanism by which divers report their uneventful dives. Training agencies are now beginning to share data on the number of divers trained, which is a very good step in the right direction. However, this information represents only part of the picture, because knowing the number of individuals certified for rebreather diving does not tell us anything about how active the divers are in terms of number and types of dives they conduct.

To address these problems for recreational scuba diving, Divers Alert Network (DAN) launched Project Dive Exploration (PDE; www.DAN.org/research/projects/pde), an ambitious project to capture log files and associated data related to the outcome of each dive not just from dives involving decompression incidents but from all dives made by participating divers. In doing so, DAN is able to get both the numerator (actual incidents) and the denominator (the full number of dives conducted in which the incidents occur). We need a mechanism within the rebreather-diver community for tracking with more confidence the total number of rebreather divers and the total number of rebreather dives being conducted, such that the reported accidents can be put into appropriate context. Specifically, we need to support DAN in expanding its PDE effort to include more specific information about rebreather dives so we can start to get a much more reliable indication of the denominators (number of active divers, number of dives per year, etc.) for rebreather dives.

Dive taxonomy and classification

When evaluating the relative risks of rebreather dives compared with recreational scuba dives, there is more to understanding the context of the dives than just the denominator. For example, many early adopters of rebreathers were from among the technical-diving community. Indeed, the advantages of using rebreathers over open-circuit scuba are far more significant on technical dives than on recreational dives. The entire concept of a "recreational rebreather" is relatively new. So it is not

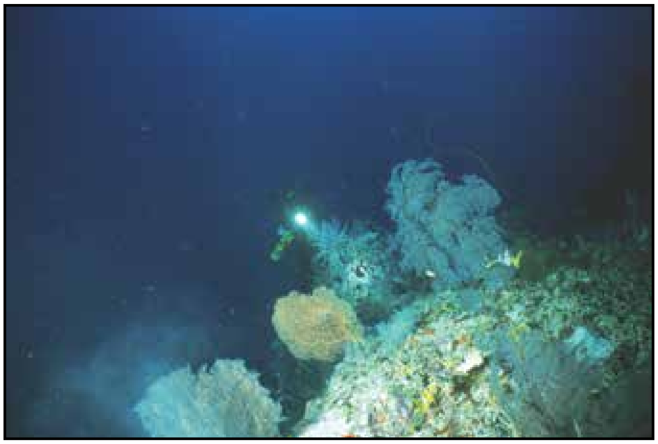

Figure 4. Bob Cranston explores a deep coral reef in Fiji using a MK-15.5 rebreather. Photo by Richard L. Pyle.

surprising that rebreather dives, on average, have tended to be more technical and/or challenging in nature than average recreational scuba dives. When preliminary data analysis suggests that accidents involving rebreather dives are five to 10 times more likely than for open-circuit dives, how much of that increased risk is due to the technology (i.e., rebreathers versus open-circuit), and how much is simply a reflection that rebreather divers tend to conduct more technically challenging (and therefore potentially more risky) dives? To address that question, there needs to be some standard metric for classifying dives according to their inherent level of risk so that we can better understand the component of risk increase that is caused by the specific technology (i.e., rebreathers per se), as opposed to risk increase inherent to the sorts of dives that rebreather divers tend to do. In other words, besides just knowing how many dives are being conducted and by whom (i.e., the denominator), we also need a standard way to qualify the nature of the dives being conducted.

We in the rebreather-diving community (and, in fact, the diving community in general) need to establish a standardized

Figure 5. A diver explores an undercut ledge on a deep reef in Rarotonga. Photo by Robert K. Whitton.

mechanism for classifying dives according to their general nature to better tease apart the actual causes and contributors to diving accidents. We already have some systems for classification of dives, but these need to be expanded and further refined. For example, labels such as "recreational," "technical," "commercial," "military," and "professional" have been applied to certain classes of diving, but these terms are still not precisely defined, and they do not allow enough precision or "granularity" for separating discrete contributors to diving risk. Other crude ways commonly used to categorize the nature of a particular dive include the maximum depth of the dive and whether or not decompression was required. Again, while these are certainly very useful parameters to include when evaluating diving accidents, they do not provide enough information to fully characterize dives according to class and potential risk factors. For example, a decompression dive could include everything from a dive that slightly exceeded the no-decompression bottom time at 60 ft (18 m) to a dive to 600 ft (180 m) requiring 12 hours of decompression. DAN is currently conducting research involving probabilistic decompression-sickness (DCS) modeling, which has the potential to better identify the specific factors that lead to decompression stress (over and above simple depths, gas mixtures, and exposure times). Such research is critical to better classify dive exposures, identify specific causes of problems, and ultimately reduce the overall risk.

There are factors that can lead to rebreather-diving accidents that do not involve decompression stress. To identify and quantify these factors we need a set of standard terms and metrics that are straightforward, objective and unambiguous and more accurately characterize the nature of any given dive. It should not be complex and elaborate (we do not need hundreds of categories of diving or discrete dive parameters), but it does need to be carefully considered. For example, the term "technical" covers many different kinds of diving paradigms; perhaps this broad term can be replaced by a series of standard terms such as "physical overhead," "multiple gas mixtures," and other similar terms that not only brand a dive as "technical" but also indicate the broad nature of the dives themselves. The standard diving taxonomy and classification should extend beyond the nature of the dives themselves and include attributes of the individual divers involved. For example, a standardized set of terms that represent both level of training and level of experience would be helpful to know in evaluating risk factors in diving.

To be effective, the classification system for diving needs to be simple (so that people will actually use it), objective (so that it is used consistently), and practical (so that it emphasizes parameters that actually do contribute to diving accidents, without being cluttered by excessive terms). Most important, it must be both stable (to allow long-term analysis of trends over decades) and universally adopted. DAN has already put a lot of thought into this for open-circuit recreational diving.

What is needed is to extend that to include more technical dive paradigms in general and rebreather diving in particular. Therefore, DAN and the Rebreather Education and Safety Association (RESA) should coordinate with others in the technical-diving community to discuss and identify the best ways to classify dives and the best terms to use (and how, precisely, to define them) so that future dives and diving accidents can be more objectively (and usefully) analyzed going forward.

Figure 6. A team of research divers with the University of Hawaii conduct an experiment on corals 280 ft (85 m) deep off Maui, while the University's Pisces submersible looks on. Photo by Richard L. Pyle.

Confessing near-misses

Like everyone with an ego (i.e., everyone on the planet), I am reticent to alert my friends, colleagues, and strangers to the true extent of my own stupidity. But the truth is, everyone (and I mean everyone) makes stupid mistakes from time to time. In my experience, learning from mistakes is by far the most effective way to learn. Unfortunately, when it comes to diving (and particularly rebreather and technical diving) mistakes can and do result in tragedy. As such, it is vitally important that we learn as much as we can from the mistakes of others to avoid making similar mistakes ourselves.

Figure 7. Belonoperca pylei *from the Cook Islands at 300 ft (91 m). Photo by Richard L. Pyle.*

In most cases, the only mistakes that get documented in diving are the ones that lead to serious injury or death. While important and valuable insights can be gained by carefully evaluating such accidents, they represent only a tiny fraction of the potential learning opportunities, because for every documented accident that results in serious injury or death, there are dozens, if not hundreds, of "near-misses," the vast majority of which are never adequately documented. In my own case, I have made hundreds of mistakes during my diving career, only one of which resulted in a serious injury and none of which caused my death. In some cases I have tried to candidly share the lessons learned from these mistakes through published articles, Internet-forum posts, and presentations and discussions with fellow divers. But I have done so only in a haphazard and inconsistent fashion. Many of the mistakes I have made, while instructive in some way, never make it into any documented or publicly accessible form. What our community needs is a mechanism through which near-misses and close-calls can be properly and consistently documented and publicly shared. This involves two components: first, developing a centralized repository where such information can be easily and objectively reported; and second, fostering a culture in diving that rewards rather than punishes individuals who are willing to confess their mistakes.

There have already been calls for establishing a community-wide database for rebreather-diving accidents, and recently these calls have been expanded to include near-misses. In fact, DAN has already created an incident-reporting mechanism for this (www.DAN.org/IncidentReport/). So the first component is already being implemented. But the second component (fostering a culture supportive of reporting such incidents) is the primary barrier to success. I address this in more detail below.

"Black box" log data

Modern rebreathers include electronic systems to monitor the oxygen partial pressure in the loop, control the injection of oxygen to make up for consumption through metabolism, display information to the diver, generate alarms and, in many cases, calculate decompression (among other things). These electronic systems generate and monitor a great deal of data, such as sensor readings (oxygen partial pressure, depth, temperature, etc.), control actions by the rebreather (e.g., solenoid injections), alarm status, decompression information, calibration data, and many other parameters. Being able to review and analyze all of this information is incredibly useful, so it is no surprise that most electronically controlled rebreather systems include a data-logging feature ("black box") to allow storing and capturing this information in a form that can be downloaded and examined later.

Figure 8. Richard L. Pyle decompresses from a deep research dive off Maui. Photo by David F. Pence.

As rebreather electronic systems have advanced and become more sophisticated, the amount of data processed have likewise increased. For example, the first rebreather I used (Cis-Lunar Mk-IV) logged several hundred data points (or "events") per hour of dive time. The next-generation Cis-Lunar Mk-5P logged more than a thousand events per hour of dive time. The rebreather I currently use logs between 15,000 and 25,000 events per hour (not to mention more than 1,000 events just during the four-minute predive routine). The database I maintain for rebreather log data already includes nearly 65 million data records, and that is just from a handful of test divers. As the sophistication of rebreather electronic systems continues to improve and the number of rebreather divers continues to increase, the total amount of data related to rebreather diving will start to get very large very quickly.

It is impossible to overstate the tremendous potential value of this information to individual divers, rebreather designers and manufacturers, training agencies, and the broader diving community. As a diver, I have found the information logged during my own rebreather dives to be extremely useful for refining techniques (e.g., ascent rates, effects of depth changes on the oxygen partial pressure in the breathing loop, oxygen sensor dynamics, optimal techniques for manual gas addition, etc.) and for understanding unusual circumstances or the source of alarms that I have encountered during particular dives. Besides serving as a powerful learning tool, rebreather log data has direct practical value to my diving activities. For example, the log allows me and my diving companions to pinpoint the depth, time and water temperature where a particular organism is collected, observed, or photographed, greatly improving the accuracy of information that contributes to our scientific research.

Figure 9. Richard L. Pyle deploys a float on a deep reef off Cocos Island, while the DeepSee submersible looks on. Photo by Howard Hall.

As useful as log data are for individual divers, they are even more valuable to rebreather designers and manufacturers. A big part of the reason for the dramatic increase in the amount of data logged in the latest generation of rebreathers is because of the feedback they provide to the people who design the rebreather control systems. With increasing processing power and storage capacity of modern electronics comes an increased ability to track and log large amounts of data with ever-increasing precision and granularity. This information allows rebreather developers to fine-tune PO_2 control algorithms, assess the reliability of sensor readings, generate alarms at the most appropriate times, and improve many other aspects of rebreather functionality. For example, the Cis-Lunar Mk-5P rebreather was introduced in 1997 and was among the most sophisticated underwater life-support systems of its time. During the 15-year period that I used this rebreather, there were about a dozen times when, during a dive, my own interpretation of the current PO_2 in the breathing loop differed from what the electronics calculated the PO_2 to be. Scrutiny of the log data after each of these dives revealed that, in every single case, my assessment of the loop PO_2 was correct, and the rebreather's was wrong. Thus, at the time, even the most advanced rebreather PO_2 control system available was no match for a well-trained diver when it came to interpreting the actual PO_2 in the breathing loop.

However, the same techniques we used to determine from the black-box log data that my assessment of the PO_2 was correct were later incorporated into a series of algorithms that improved the core logic of the rebreather control system. After several iterations of continued development (along with increasing data resolution and CPU processing power), the dynamic has changed. There have been about a half-dozen cases when using my current rebreather where my interpretation of the loop PO_2 differed from that of the rebreather electronics. But now, in every single case, objective evaluation of the data revealed that the rebreather was correct, and my own interpretation was wrong. The fact that the oxygen control system is now more reliable than a well-trained rebreather diver is almost entirely due to the existence of downloadable log data accumulated over thousands of dives, which allowed the development of more reliable and accurate logic and

Figure 10. Richard L. Pyle dives with a rebreather in Fiji. Photo by Cat Holloway, NAI'A Fiji.

control algorithms. These algorithms go far beyond using sensor data to simply measure the PO_2 of the breathing loop; they are now used to evaluate the reliability and proper functionality of the sensors themselves in real-time during the dive.

Of course, there are other reasons why log data can be extremely valuable to rebreather manufacturers. Among the most obvious is the ability to analyze problems encountered by the end-user divers. Data logs are extremely helpful for service technicians and other representatives for a rebreather manufacturer to use in trouble-shooting issues that divers have had using their products. Aggregated data from end-users are also extremely valuable in helping rebreather manufacturers understand how their devices are being used in the "real world" and thereby prioritize design modifications, add new features and develop new products. Training agencies could likewise benefit dramatically from such feedback based on dives conducted by divers certified by their instructors.

Perhaps the most important value of having access to such rebreather log data is to the entire community as a whole: for the purpose of accident analysis. There is a reason that the aviation industry places so much emphasis on "black-box" data when evaluating crashes and other accidents. Such data logs are much more reliable than eyewitness accounts (especially when there are no witnesses), and they can provide very detailed information leading up to an incident. Such data are invaluable for understanding the series of events that led to an accident and therefore represent critical feedback to manufacturers (in cases where control systems can be improved), training agencies (in cases where divers made bad decisions), and individual divers (in the form of sobering lessons to learn from). The entire rebreather community stands to benefit from more accurate and objective interpretations of accidents so that more intelligent steps can be taken to reduce such accidents in the future.

Establishing a culture of data sharing

This last point is by far the most important. The technical infrastructure to support the documentation of rebreather dives and capture rebreather log data is relatively straightforward. The hard part is getting the relevant players — divers, manufacturers, training agencies, and data analysts — coordinated and (both more important and more challenging) *willing to share information*. The basic strategy for achieving this is to reduce the barriers to participation in data sharing and increase the benefits.

To address both the denominator issue and capitalize on the real potential value of the black-box data, we should focus on the model already established by DAN's PDE program. When it was originally launched in 1995, the stated goal was to capture a million dive logs (including downloaded data from dive computers) from recreational scuba divers. After nearly two decades, only about 20 percent of the original goal has been achieved. Given the number of divers in the world and the number of dives being conducted, we can infer that only a very small fraction of divers are participating in the program. I believe that we can significantly boost the level of participation

Figure 11. Richard L. Pyle encounters a large coelacanth nearly 400 ft (122 m) deep off South Africa. Photo by Robert K. Whitton.

Figure 12. Richard L. Pyle decompresses from a deep research dive off Maui. Photo by David F. Pence.

in PDE through participation by the rebreather community, but this will require actions on the part of all of the relevant players (divers, manufacturers, training agencies, and data analysts).

The role of the data analysts (i.e., DAN) is relatively straightforward, and the infrastructure to support it is largely in place. The main task is for DAN to coordinate closely with RESA and/or individual rebreather manufacturers on expanding the data model for PDE to accommodate the specific kinds of information that will be useful for evaluating rebreather dives — both in terms of how the dives themselves are recorded and what additional kinds of information derived from downloaded log files should be included within the PDE protocol and data model. Preliminary discussions are already under way for establishing appropriate data standards, but these need to be more inclusive of multiple manufacturers, perhaps as a task coordinated by RESA.

Likewise, the role of the training agencies is already beginning to be fulfilled through renewed commitments to share information about numbers of certified instructors and divers. Efforts on this should be continued through ongoing dialog among the training agencies and with DAN to ensure consistency of reported data and to mitigate any concerns from individual training agencies about how the submitted data will be used and how to prevent abuse of the information.

The main area that our community needs to focus on is addressing the barriers and incentives for rebreather manufacturers and rebreather divers to participate in sharing their data. Barriers for participation by manufacturers include protecting proprietary information from exploitation by competitors, avoiding unnecessary exposure to liability, concerns about how data might be exploited or misused by detractors and competitors, and the costs associated with the technical implementation necessary for providing the actual data to DAN. Barriers for participation by individual divers relate to concerns about personal privacy, concerns about the diver's reputation in terms of numbers and kinds of dives conducted, and the actual time involved in documenting the information in a form that can be easily transmitted to DAN. These are all legitimate concerns and have generally outweighed the perceived benefits that can be gained through data sharing. The task at hand is to reduce all of the barriers such that the concerns are adequately addressed and also to increase the perceived benefits for participation by both manufacturers and individual divers.

A ROADMAP FOR IMPLEMENTATION

The first and most basic task is to encourage all manufacturers to include data-logging features within the electronics of their rebreather systems. Most rebreather manufacturers already do this, and RESA should help encourage those who do not yet do this

Figure 13. Richard L. Pyle photographs objects in Fiji while wearing a rebreather. Photo by Cat Holloway, NAI'A Fiji.

to add this basic feature to their rebreather designs. One potential concern that some manufacturers have privately expressed to me is that the existence of log data could potentially be used against them in a lawsuit. In my own experience, in every single case involving a rebreather fatality where log data were available, the data exonerated (rather than incriminated) the rebreather design itself as a primary contributing factor. Conversely, in cases where log data are not available, the benefit of the doubt often does not favor the rebreather manufacturer as strongly. It would be very helpful if experts with experience in legal cases involving rebreather accidents could analyze the history and document to what extent having "black-box" log data have supported the manufacturers in such cases. If my own experience reflects the broader history, this should go a long way to encouraging manufacturers that do not currently provide downloadable log data to add this feature to their rebreather designs. In cases where data logging is not intrinsically part of the rebreather itself, then end-users

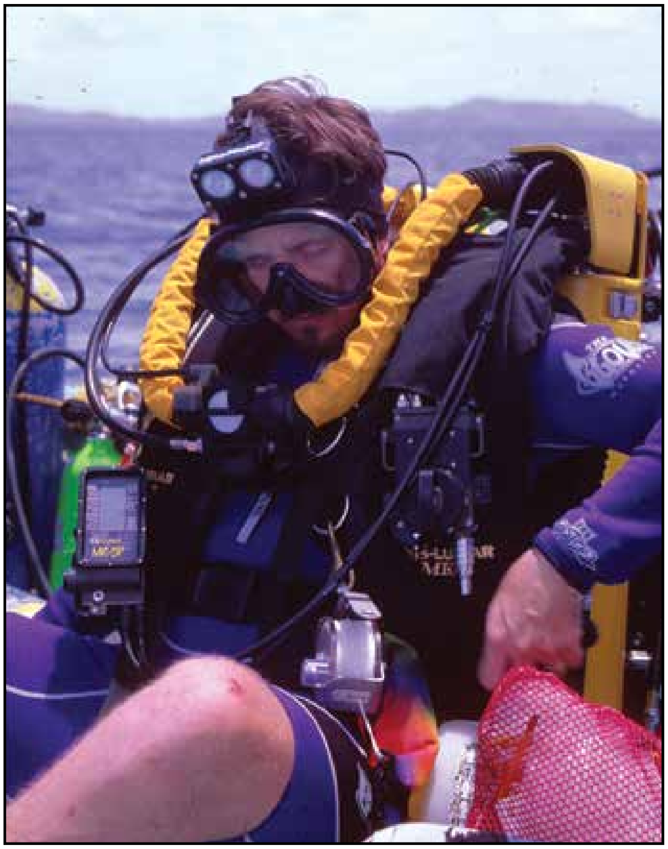

Figure 14. Preparing for a rebreather dive in Palau. Photo by Ken Corben.

Figure 15. Richard L. Pyle prepares to descend a vertical drop-off. Photo by Robert K. Whitton.

should be encouraged to use third-party dive computers that support both rebreather diving and data logging so they can capture data from the dives even when using rebreathers that do not include a data-logging feature.

The next step is to encourage and facilitate the downloading of data from rebreathers and third-party dive computers used with rebreathers onto the diver's personal computer or portable device (smartphone, tablet, etc.). Although the memory space for recording log data on the rebreather or dive computer electronics can be quite large, it is generally not large enough to capture an individual diver's entire history of dives. At some point, the memory space used to store older dive-log data is overwritten with newer log data. Therefore, the individual divers need to be encouraged to regularly download data from their rebreather or dive computer onto a larger and more permanent storage space, such as the hard drive of their personal computer. Manufacturers can help facilitate this by developing software and connection interfaces that make this process very easy for divers to implement and include helpful features that support what many divers like to do. For example, underwater photographers and videographers often like to know the depth where any particular image was taken. The problem is that internal clocks in rebreathers and cameras are often out of sync, making this task difficult. Including simple features in the rebreather download software to allow divers to establish time offsets between their rebreather clocks and their camera clocks can enhance the utility of the downloaded rebreather data for the diver, thereby increasing the benefits for taking the time to download the data from the rebreather in the first place. There are many other ways that rebreather software can be designed that help encourage divers to capture the raw data from their rebreathers onto their personal computers. Additionally, such software should be designed to encourage the end-users to capture the kinds of information that PDE requires, thereby enhancing the value of the data for later submission to DAN. Finally, the software should assign permanent and globally unique identifiers to individual dives and individual divers such that data are encoded with these identifiers as close to the source as possible. Ideally, such

Figure 16. Richard L. Pyle tests an experimental Poseidon rebreather. Photo by John L. Earle.

identifiers would be assigned within the rebreather or dive computers themselves, but in cases where that is not possible, then the identifiers should be assigned at the time the data are downloaded. Based on my experience within the biodiversity informatics community (where the subject of globally unique identifiers, or GUIDs, is among the most fundamental topics in leveraging the power of data), I would recommend that these identifiers be 128 bits in size and be generated and rendered in accordance with standards for universally unique identifiers (UUIDs; see http://en.wikipedia.org/wiki/universally_unique_identifier).

After the data have been captured from the rebreathers and/or dive computers and permanent globally unique identifiers have been assigned, the next step is to make those data available to the data analysts at DAN. While this could be done directly from the divers to DAN, I believe that a much better strategy is to process the data from end-users through the manufacturers and then secondarily from the manufacturers to DAN. There are several reasons for this, but the primary reason is that the manufacturers are the ones who stand to benefit the most from data gathered by end-users of their products and therefore are in the best position to provide incentives to divers to cooperate. One such incentive might be to provide more detailed analysis of log data transmitted to the manufacturer than divers can get from simply looking at the data themselves. Most divers simply want to look at a few basic parameters such as depth and perhaps water temperature, PO_2, and system warnings. Modern rebreather logging systems capture much more detailed data than just these things. While most of those additional data would be unintelligible to the end-user diver, the manufacturer would be able to process the information and provide feedback to the diver for things such as general health of oxygen sensors, patterns of gas consumption, ascent rates, and other parameters of the dive including why certain alarms were triggered and how the diver can prevent such alarms in the future. The manufacturer could also provide recommendations on how to improve techniques and dive habits to make dives both safer and more enjoyable. This could be coordinated through an online social-networking environment such that divers could share dive logs with their dive buddies and friends (either directly or through posting dive reports to major social networks such as Facebook, Google+ and others). Such a system could allow divers who have specific sorts of problems (e.g., persistent PO_2 spikes or excessive gas-consumption rates) that can be recognized in the downloaded log data to be provided with links to specific threads on online discussion forums such as RebreatherWorld that discuss those same sorts of issues. Divers could also be shown where they stand among the broader community in terms of patterns of diving and rewards (in the form of discounts or coupons or even just positive acknowledgment) to those divers who provide complete and consistent data. The possibilities are nearly endless, and my hope is that in the same way that social networking in general has been the dominant force in driving the utilization of the Internet, an analogous information and networking structure can be used to dramatically encourage divers to capture and share their dive data. Training agencies can also play an important role in emphasizing to students why it is so important for them to share their data and establishing a social norm for doing so, so that divers understand the value and benefits of doing so from the very beginning of their dive careers.

Of course, providing incentives to divers to share their data addresses only part of the problem. The other part is removing the barriers. Concerns about privacy are probably among the greatest of these barriers, and there are two simple steps that can be taken to alleviate such concerns. The first is for manufacturers, in developing their data-collection infrastructures, to establish clear and strong privacy policies for how the data will be used and shared. These should emphasize that sharing such information will not lead to marketing solicitations (unless the divers explicitly opt-in to such services), nor will the downloaded data be used to nullify product warranties or reprimand the divers in any way. This may seem like an important component for capturing the data from a manufacturer's perspective, but the value of having the data (and, specifically, large volumes of data) to the manufacturers will be far, far greater than maintaining the ability to void warranties or scold individual divers. Instead, gentle reminders might be provided to divers who routinely engage in unsafe or unwarranted practices about the hazards of doing so without explicitly voiding the warranty or in some way punishing the diver for bad behavior.

The second way to address concerns about privacy is to anonymize the data. For various analytical reasons, it is useful to know that that the same person conducted a given set of dives, and it is also useful to know certain attributes about the individual diver (such as age and other factors). Thus, it is important to link dive-log data to an individual person. However, there is no value in identifying who that person is. Going back to the earlier comments about globally unique identifiers, a simple way to anonymize divers is to tag their dives with one of these numbers but then strongly protect information about who that diver is. Manufacturers should give end-users the option of allowing the manufacturer to establish the link between the identifier and the person or not. When the link is made within the manufacturer, there should be very strong protections to make sure that the link is not released outside of the manufacture (e.g., to DAN or to other divers). Doing so will help reduce concerns about privacy that might otherwise discourage end-user divers from sharing their data.

Similarly, the primary barrier to documenting near-misses is a general unwillingness for divers to confess their mistakes. The reasons for this are obvious. First, there has historically been a pattern of public vilification for errors in judgment when it comes to diving. Going back decades, certain "personalities" on various email lists and Internet forums discussing diving have established a culture of criticism against those who report their mistakes. The level of "armchair quarterbacking" in such venues has at times reached near-epidemic levels. Respected leaders in the rebreather community can set a better tone, focusing less on admonition and more on praise and constructive commentary. Another reason some people are reluctant to share incidents publicly is out of fear of appearing hypocritical. This applies especially to well-known individuals in the community, who are wary of damaging their reputations. One of the main examples of this is that by sharing details about mistakes, established divers might reveal that they do not always practice what they preach. This certainly contributes to my own reluctance for full disclosure of all incidents. It would be helpful if our community embraced the reality that all divers are humans, and all humans are guilty from time to time of acting in contrast to the practices that they recommend to others. Often such violations of one's own personal rules represent the foundations that lead to an accident. So when someone reports an incident that involves decisions that run counter to what that same person may have regularly espoused, the reaction should not be to brand the diver a hypocrite but instead praise the person for having the courage to admit the lapse and thereby allow others to learn. In general, the culture among rebreather divers should recognize that people who routinely report near-misses and close-calls should not be seen as prone to making more mistakes than other divers; they should simply be seen as being more honest than other divers (and be praised for that honesty).

The final step is to allow the data collected through manufacturers to be shared with DAN. The technical mechanisms and implementation policies associated with doing this should be developed between manufacturers and DAN through RESA. Part of this will involve policies for how the data will be made available through DAN to external parties. In the same way that divers may be reluctant to share data about their own dives publicly, manufacturers may be reluctant to share data with their competitors through DAN. Although the current trend is to use diver-accident databases to analyze accident rates in the context of specific models and brands of rebreathers, and there is some legitimate value in doing so, it is far more important for the community in general that the broader data be captured and made available for analysis. To whatever extent manufacturers might be reluctant to share data from their respective rebreather-diving communities with DAN, a possible solution would be to anonymize the rebreather brand or model in the data contributed to DAN. This would limit the ability to correlate specific kinds of problems with specific models of rebreathers, but if it means increased participation by manufacturers who would otherwise be unwilling to share data, the trade-off may be worthwhile.

SUMMARY

The rebreather-diving community has come a long way during the past two decades. As rebreather technology becomes ever more commonplace within the context of recreational diving, the urgency for seriously addressing the apparent discrepancy in risk that rebreather divers incur compared with recreational scuba diving likewise increases. The only serious way to address this problem is through objective analysis of more and better data. Details about implementing the above data-gathering steps should be defined and established through a cooperative effort involving rebreather divers, rebreather manufacturers (through RESA), major training agencies, and DAN. DAN's PDE research program should serve as a model and template for implementing this effort, including the development of data standards for classifying dives, and for capturing data. Having such standards and infrastructures in place is only one part of the solution. The other part involves changing the core culture among rebreather divers to reduce or eliminate the barriers to sharing data and endorse or support the establishment of incentives for doing so.

In a recent issue of *Time* magazine, Microsoft founder and former CEO Bill Gates wrote, "All the good business leaders I know are maniacal about measuring things. Measurement is a big part of mobilizing for impact. You set a goal, and then you use data to make sure you're making progress toward it. If you want a better world, you need to constantly take stock." He was talking about improving global health, but his point applies to any situation in which we want to improve something about the world we live in.

The last two sentences of Bill Gates' piece in *Time* perfectly capture the message I am trying to convey through this article: *"We can afford to make time for gathering data and crunching numbers. In fact, when it comes to saving lives, we can't afford not to."*

Amen.

Richard L. Pyle uses a Cis-Lunar MK-5P rebreather in Vanuatu while collecting specimens from a deep coral reef. Photo by John L. Earle.

OXYGEN SENSOR TECHNOLOGY FOR REBREATHERS

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ABSTRACT

Galvanic PO_2 sensors are the core elements for PO_2 control in closed-circuit rebreathers. These sensors are prone to fail. The consequence of incorrect PO_2 readings is a faulty PO_2 control with a PO_2 inside the loop possibly outside of life-supporting limits. Too low or too much O_2 is believed to be one of the main causes for rebreather fatalities. Galvanic sensors fail frequently and in different ways (current limitation, corroded contacts, broken contacts, etc.) Different strategies were developed to address this problem: Voting algorithm uses several sensors and compares their signal to each other. True sensor validation, in contrast, works in principle also with just one sensor, which is validated in constant time intervals. Temperature influences sensor performance in multiple ways. On the one hand, the sensor current is increased by typically 2-3 percent per K. Next, the response time decreases with increasing temperature. Temperature effects on sensors should be understood to design rebreathers and carry out sensor tests in a safe way. Last, but not least, sensor temperature also effects the lifetime of PO_2 sensors. This paper also introduces future sensor technologies, which are currently still on a pure academic level. New sensor technologies include optical sensors, solid-state sensors and advanced signal processing for conventional galvanic sensors.

Keywords: current limitation, galvanic sensors, optodes, personal protective equipment, solid state sensors

INTRODUCTION

Personal protective equipment (PPE Directive 89/686/EEC) is necessary whenever a person is exposed to a life-threatening or a non-life-sustaining environment. A major part of life-support systems is the breathing apparatus necessary to supply breathing gas when an individual is exposed, for example, to water (diving) or to hazardous gases (firefighting).

Closed-circuit rebreathers have many advantages in comparison to open-circuit systems (Sieber and Pyle, 2010). In an oxygen rebreather (NOAA, 2001) a person exhales into a bag — the so-called "counterlung." A scrubber removes carbon dioxide (CO_2), and fresh gas is added to replace metabolized oxygen (O_2). This recycled gas is then inhaled by the diver again. In the case of an O_2 rebreather, the circuit contains mainly O_2 and traces of N_2. Thus, the partial pressure of O_2 (PO_2) inside the circuit is dependent on the ambient pressure by Dalton's law. Such a system has the advantage of maximizing the gas efficiency up to 100 percent. O_2 rebreathers can be designed as purely mechanical systems and are robust and reliable. Many rebreathers require mixture of O_2 and other gases for respiration. For example, in the case of firefighting, one would tend to avoid breathing systems containing pure O_2 because of the increased risk of combustion. In diving applications, use of pure oxygen is only advisable to a maximum depth of 6 msw (20 fsw), as O_2 becomes toxic at partial pressures greater than 1.4-1.6 bar. A diluent gas is used to lower the partial pressure of O_2 (Mount et al., 1992). This diluent gas is typically air or so-called trimix, containing He, O_2 and N_2. Closed-circuit rebreather systems that use a gas mixture cannot be purely mechanical, since in that case PO_2 monitoring and regulation is required. Wet-electrochemical galvanic PO_2 sensors are used to measure PO_2. A manual or automatic control loop is used to keep the PO_2 at a constant level by replacing metabolized O_2 with fresh O_2 from a supply tank. Within the European Union rebreathers are classified as Category III Personal Protective Equipment.

It is imperative that oxygen sensors measure partial oxygen pressures correctly because the limits where the user becomes injured are fairly narrow. Incorrect PO_2 readings from faulty PO_2 sensors can lead to too little or too much O_2 — both life-threatening conditions. In fact, incorrect PO_2 in the rebreather loop is believed to be the main cause for many fatalities.

METHODS

Galvanic PO_2 sensors

Many medical life-support systems and all rebreather-diving systems use galvanic O_2 sensors, which basically operate like a metal/air battery (Lamb, 1999) (Raymaekers) (Alaphasense) (Chang et al., 1993). O_2 gets dissociated and reduced at the cathode to hydroxyl ions. Those pass through the electrolyte and oxidize the metal anode. A current, which is proportional to the rate of O_2 consumption, is generated when the cathode and anode are electrically loaded with a resistor (typically between 50 and 300Ω).

Cathode reaction:
$O_2+2H_2O+4e^- \Leftrightarrow 4OH^-$

Anode reaction:
$2Pb+4OH^- \Leftrightarrow 2PbO+2H_2O + 4e^-$

Overall cell reaction:
$2Pb+O_2 \Rightarrow 2PbO$

The relation of the cell current — thus the amount of electrons — is linear to the amount of O_2 reduced at the cathode. The number of O_2 molecules that are reduced in a simple cathode-electrolyte-anode setup is not linearly dependent on the PO_2 in the gas and depends on many parameters, such as the O_2 coverage, the overpotentials at the electrodes, etc. To achieve a linear relationship between sensor current, the electrochemical engineer applies a trick. A diffusion barrier is mounted in front of the cathode. It limits the amount of molecules that can reach the cathode. All O_2 molecules at the cathode get reduced, and therefore the PO_2 directly on the cathode is always close to zero. The amount of molecules reaching the cathode follows Fick's law of diffusion and is proportional to the PO_2 in front of the sensor membrane. Thus the current of the (ideal) sensor is now only dependent on the PO_2 in front of the sensor membrane. Galvanic PO_2 sensors typically used in rebreathers include a load resistor. Thus, the electronics in the rebreather measure a sensor voltage and not a current. This voltage is typically between 7-28 mV for a PO_2 of 0.21 bar — dependent on the type and age of a sensor.

The diffusion of O_2 molecules is a linear function of the PO_2 in front of the sensor membrane; however, it is temperature dependent: The sensor current rises about 2-3 percent per K. In practice, electronic boards are incorporated in the sensor design, which are situated behind the sensor cell. These boards include the load resistor in parallel to the sensor cell temperature sensitive electronic components (NTC, which stands for a resistor with negative temperature coefficient) to achieve temperature compensation.

PO_2 sensor cells especially designed for the use in rebreathers use thermal conductive paste between the temperature compensating circuit and the sensor cell to achieve same temperatures for sensor cell as well as temperature compensating element (Figure 1).

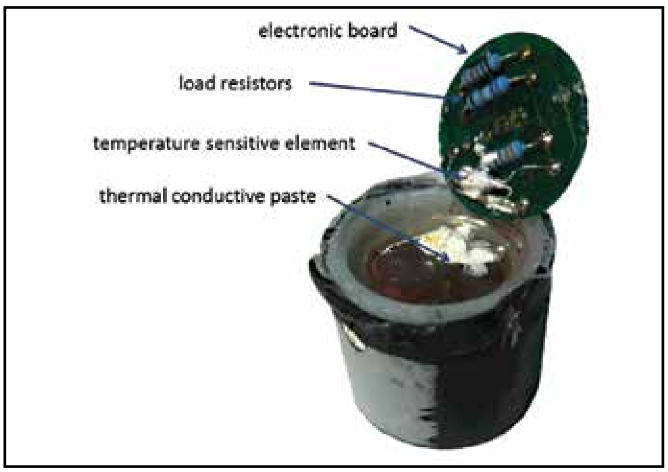

Figure 1. Disassembled galvanic PO_2 sensor. The electronic board includes load resistors and a temperature sensitive element, typically an NTC.

There are PO_2 sensors for medical applications that do not include thermal conductive paste. I advocate not using such sensors because the sensor cell could have a different temperature than the temperature compensating board, which then can further lead to incorrect measurements.

Special care also has to be taken in the design of a sensor support such that no temperature gradient within the cell can occur. This might be the case, for example, when sensors are situated in a housing or the sensor membrane is located in the gas stream exiting the scrubber and the electronic board and the connectors in the gas stream entering the scrubber.

Temperature does not only influence the sensor current but also the sensor signal rise time. The sensor signal rise time is usually given as t90 (time after a step change after which the sensor achieves 90 percent of the final sensor signal). Values for t90 are usually between 6 and 15 seconds in the datasheets. These values, however, are only valid for measurements at room temperature. Cold sensor cells are much slower, warm censor cells are much faster. Figure 2 shows sensor response times dependent on the sensor temperature.

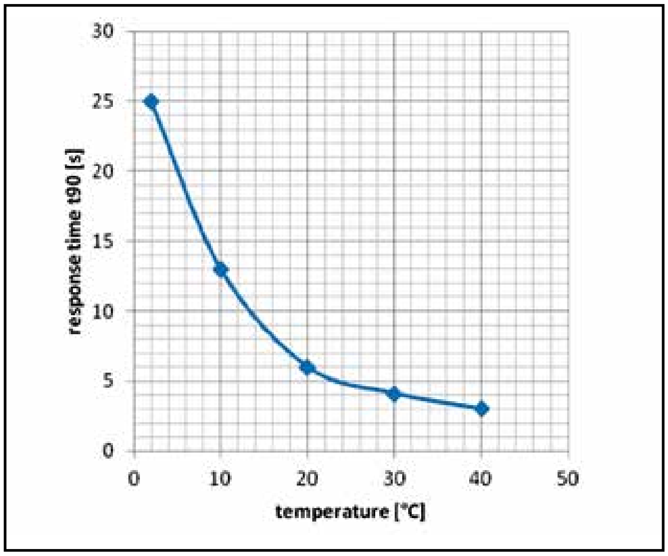

Figure 2. Response time of galvanic O_2 sensors depends on temperature.

In the ideal galvanic PO_2 sensor, the electrical current is a direct function of the O_2 concentration (or partial pressure) in front of the sensor membrane, as the rate at which O_2 reaches the cathode is only limited by the diffusion barrier. It is obvious that once the anode material is oxidized, the output current drops to zero and the cell has reached the end of its lifetime. As the oxidation rate depends on the PO_2 in front of the sensor membrane, the lifetime is measured in oxygen hours (see below) but depends on many other factors such as storage temperature and humidity.

New O_2 sensors used in diving and medical applications can produce linear signals up to more than 4.0 bar of PO_2. Aging of the anode leads to a reduced active surface area that then becomes current-limiting. Such cells become non-linear above a certain threshold and do not give the expected output for high PO_2s that, in a life-support system, may be life-threatening. Such a PO_2 sensor is usually described as a current-limited PO_2 sensor.

Current-limited sensor cells are life-threatening in cases where the current limitation starts at a PO_2 below the setpoint of the rebreather. In this case the rebreather electronics injects too much O_2. Other failure modes for this kind of sensor include mechanical damage, e.g., broken connection wires, corroded contacts, or perforated membranes that may lead to a loss of electrolyte.

Galvanic O_2 sensor lifetime

O_2 sensor cell manufacturers use two ways of specifying the lifetime of their sensors. Some state an amount of months in room temperature and in air (24-48 months sensor life). Others specify in a special unit: volume % O_2h. Typical values are 500,000-1,000,000 Vol%O_2h. A sensor with 1 million Vol% O_2h has therefore a lifetime of 2,000 days in air at 20°C (68°F).

$$\frac{1000000}{21\% \times 24h} \approx 2000d$$

From this calculation one might conclude that storing PO_2 in N_2 between dives might help extend the sensor's total lifetime. However, in such a case the sensor current will drop to zero because no O_2 is available. This may further lead to passivation of the electrodes, which again can lead to sensor failure. Therefore, I do not recommend storing a galvanic PO_2 in N_2 or sealing off the sensor's membrane.

If the sensor is stored at a higher ambient temperature, for example, 30°C (86°F) instead of 20°C (68°F), then the sensor current is higher, and therefore the lifetime is decreased.

$$\frac{1000000}{21\% \times 24h} \times 1.03^{(20°C-30°C)} \approx 1500d$$

In contrast to these values, in diving an O_2 sensor lasts only about 12-18 months on average. Over a period of 18 months a diver might spend, for instance, 150 hours in diving (loop PO_2 of 1.2 atm, in the calculation a PO_2 is expressed with 120 percent), in the rest of the time the sensors are stored in room temperature. The dives result in:

$$120\% \times 150h \times 1.03^{(20°C-40°C)} \approx 18000Vol\%O_2h$$

The storage time (18 months ~ 540 days) results in:

$$21\% \times 24h \times 540d \approx 272000Vol\%O_2h$$

This sum, ~ 300 000 Vol% O_2h value, is by far lower than values typically specified by the sensor manufacturers. The life of PO_2 sensors in a rebreather is far less than what is stated in the datasheet. There must be some kind of accelerated aging of O_2 sensors in a rebreather.

Why do PO_2 sensors fail? And why do they fail or age in such a short time? PO_2 sensors used in rebreathers were not primarily designed for rebreather divers; they are mostly sensors designed for medical applications. The sensors are designed to last under normobaric conditions and ambient temperatures. In diving, however, the sensors are exposed to high ambient pressures, hyperbaric PO_2 levels, high temperatures, moisture, salt and seawater, high humidity and sometimes even high PCO_2. In addition, sensors are exposed to mechanical shock and vibration, especially during transportation to the diving site in a car or on a boat. Sensors in a rebreather are not used as specified in a datasheet in laboratory conditions; instead, they are exposed to very harsh environments. In a rebreather, PO_2 sensors are abused, and it is not a surprise that sensors fail earlier than specified in a datasheet.

Voting logic is the dominant concept on the rebreather market to address PO_2 sensor problems. The basis for such an approach is that sensors fail independently. This is, however, not the case: O_2 sensors in a rebreather are subject to a common abuse. If sensors are installed together in a rebreather and they have the same diving history, then this also means that their history of "abuse" is the same. Understanding that this common abuse is making PO_2 sensors fail earlier lets us further conclude that O_2 sensors do not fail independently anymore. Therefore, having three or more O_2 sensors does not provide triple or higher redundancy, as the sensor failures are connected to each other. In other words, if one O_2 sensor fails, there is a high chance that a second will also fail.

True sensor validation of galvanic PO_2 sensors

Before developing sensor systems for diving, I worked in medical instrumentation research and development where we focused on blood gas analyzers. These systems are able to analyze a wide range of parameters from a few droplets of blood. The core component of these devices is a measurement chamber with several electrochemical sensors. Although these sensors are typically smaller than rebreather sensors, the working principle is similar. Interestingly, despite medical sensors being part of a critical health-care system (an incorrect measurement could lead to the wrong diagnosis or treatment), only one sensor is typically installed for each parameter measured. It is known that multiple sensors can fail in parallel at the same time, and therefore adding additional sensors would not increase the robustness and accuracy of the system to a level that is required for such life-critical system. Instead, a calibration and validation system is added. This system flushes the sensors with a calibration solution with known ingredients in certain time intervals. The sensor response to the calibration solution is measured and compared to the calibration values. This is similar to a diluent flush in a rebreather. The sensor readings are compared to a known value. In cases of deviations the sensor is known to be faulty, or possibly a recalibration is carried out.

The medical industry uses multipoint calibration to cover the whole span of possible measurement results. Rebreathers and rebreather divers do not usually do that. Instead, extrapolation is used. PO_2 sensors are calibrated on the surface with air or PO_2 at ambient pressure of 1.0 bar, but then during the dive a setpoint higher than 1.0 bar is used. This is, however, a dangerous assumption based on extrapolation — there is no evidence that a sensor that gives correct readings at 1.0 bar PO_2 can measure correctly above 1.0 bar because the sensor might be current-limited.

There are several solutions commonly used to tackle this problem. One is based on pressure pot testing of sensors. A PO_2 sensor is placed in a small hyperbaric test chamber and exposed to a PO_2 >1.0 bar. This can be done either with compressed air or O_2. In our lab, we have a sensor test chamber that works up to 20 bar and therefore can be used to expose a PO_2 sensor to a PO_2 of ~4.0 bar when using air.

Discussion with rebreather divers who use pressure pot testing reveals the common opinion that if a PO_2 sensor can read an increased PO_2 in a pressure pot correctly, it also does that during diving. Thus, many divers test their sensors up to 1.6 bar. Medical sensor engineers know that it is essential to calibrate and test a sensor under the same circumstances in which they are used during operation. Pressure pot testing, however, ignores this as sensors are typically tested at room temperature, and the temperature of a PO_2 sensor inside the loop (after the scrubber) can reach temperatures up to 45°C (113°F).

The maximum electrical current that can be produced by an O_2 sensor depends on the PO_2 and the state of the anode. If the anode is exhausted, current limitation occurs, and not all available PO_2 can get reduced. A diffusion barrier membrane limits the amount of molecules able to reach the cathode — therefore the amount of current that can be produced. This diffusion strongly depends on temperature. At 45°C (113°F) much more O_2 molecules can diffuse through the membrane than at room temperature. An O_2 sensor with a partially exhausted anode can measure correctly 1.6 bar at room temperature but possibly fails to read 1.6 bar correctly at 45°C (113°F). We also test PO_2 sensors in pressure pots, however, we use as acceptance criterion linearity to twice of the setpoint (1.2 bar setpoint, then we test to 2.4 bar).

Another common way for testing PO_2 sensors for linearity in the hyperbaric region is to perform a PO_2 flush at 6 m (20 ft). Here the diver checks if the PO_2 sensors can read 1.6 bar PO_2 correctly. The advantage of this method is that the sensors are checked in the same environment in which they are used. It is important to understand that the sensors might be relatively cold at the beginning of the dive compared to the end of the dive. In winter, for example, one might store the rebreather in the trunk of the car and go diving in the morning, in which case, the sensors will start with a rather low temperature even if a prebreathe of several minutes was correctly carried out.

Several years ago we started thinking about how to automate sensor tests. Medical analyzers use single sensors together with continuous validation and multipoint calibration. The main idea was to apply this technology in rebreathers. We began developing an automatic sensor validation (Sieber et at., 2008). Additional solenoids (Figure 3) where added to allow injection of O_2 and diluent directly in front of the sensor membrane. This allows flushing just the sensor membrane with a gas with a known composition without requiring to

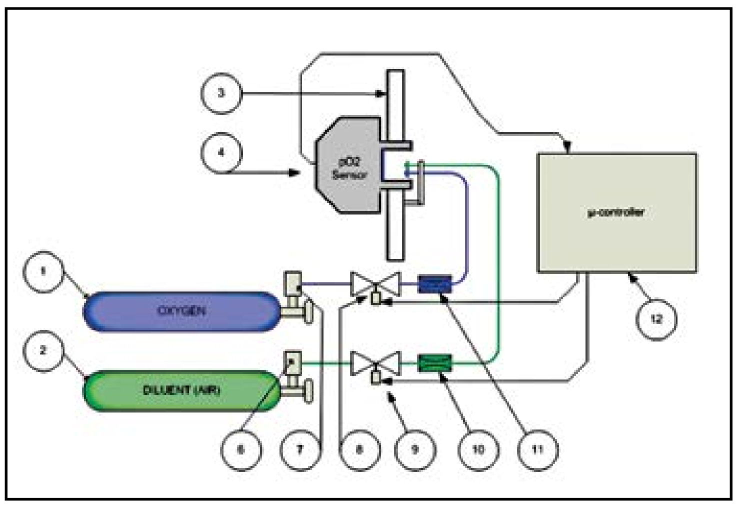

Figure 3. Schematic of our true PO_2 sensor signal validation system (1: O_2 tank; 2: diluent tank; 3: sensor support; 4: PO_2 sensor; 6,7: pressure regulators; 8,9: solenoids; 10,11: flow restriction orifices; 12: microcontroller). Reprinted with permission of Diving and Hyperbaric Medicine *(Sieber et al., 2008).*

flush the complete loop. With a few cm^3 of gas injected onto the sensor membrane, this system enables validation of the sensor in three ways:

1. Test of the sensor response to diluent (O_2 fraction in the injected diluent multiplied by the ambient pressure should be equal to the PO_2 reading).
2. Test of the sensor response to O_2 at 6 msw (20 fsw) depth (hyperbaric O_2 test, PO_2 reading should be 1.6 bar).
3. Test the sensor for signal rise time (t90).

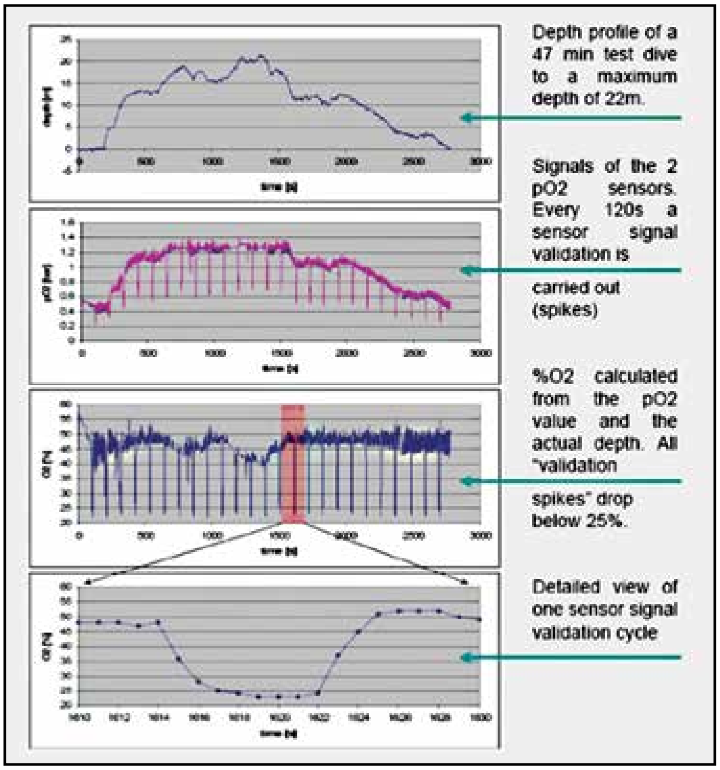

Figure 4. Data from a 100-minute test dive (6,000 seconds) in the Mediterranean Sea to a maximum depth of 22 m (72 ft). (A: depth profile; B: PO_2 sensor signals of two sensors; C: calculated fO_2; D: one validation cycle) Reprinted with permission of Diving and Hyperbaric Medicine *(Sieber et al., 2008).*

Figure 4 shows data from a 100-minute test dive in the Mediterranean Sea. A sensor signal validation with diluent (in this case it was air) was carried out each 120 seconds. Additional tests included flushing the sensors with O_2 to check the sensor for linearity in the hyperbaric region. The technology was implemented in a commercially available recreational rebreather (Shreeves, 2009).

Future of O_2 sensors

O_2 sensors play the key role in rebreather O_2 control. Advances in microsystems and microtechnology enable the development of new kinds of PO_2 sensors for rebreathers, although many approaches are still on a purely research level. In the following section three different sensor technologies are discussed briefly.

Smart galvanic O_2 sensor

Our European project LifeLoop (EU FP7-People-IEF-2008 (Marie Curie) action, project nr. 237128) focused on development of new sensor technologies for rebreathers. A novel approach for reading galvanic PO_2 sensors was to replace the analog electronic board of the O_2 sensors with low-cost microprocessor-based multifunctional sensor electronics (Figure 5). The microcontroller board measured sensor current, sensor temperature, and calculated the PO_2. Sensor calibration values can be stored directly on the microcontroller board. A special circuit applied voltages to the sensor and measuring the responding current to detect current-limited cells without exposure to hyperbaric oxygen in a pressure pot or requiring additional solenoids as in Figure 3. Further advantages of this smart concept included a unique serial number for each sensor's electronics and an O_2 hour counter.

Figure 5. Prototype of our "smart" galvanic O_2 sensor.

Optical O_2 sensors

Optodes are optical oxygen sensors in which a chemical layer is illuminated and fluoresces at a different wavelength. Optical filters separate the illumination and fluorescence signals. Oxygen quenches the fluorescence and reduces the output signal. Optodes are most sensitive when no or trace amounts of O_2 are present, and sensitivity decreases with increasing PO_2, but recently developed fluorescence pigments allow reliable measurement of PO_2 above 1.0 bar (Borisov et al., 2008). In our laboratory we have successfully tested optodes up to 2.0 bar PO_2 and with the first prototype were able to achieve an accuracy of 2-3 percent from 0.2-1.6 bar PO_2. The response time of the sensors was less than 100 ms.

There are several interesting approaches to integrating optodes in rebreathers. Fitting them between the mushroom valves in the mouthpiece would allow assessment of inspired as well as expired PO_2. As they may only cost a few cents in mass production, they might be designed as single-use devices in which a chemical layer of sensor film could be mounted on an adhesive and changed before each dive. Alternatively, the sensor film might be sprayed or printed onto CO_2 absorbent cartridges (Fisher et al., 2010). Each time the CO_2 cartridge was changed, the O_2 sensor would be replaced.

Solid-state O_2 sensors

An alternative to liquid electrolyte sensors is solid-state technology based mainly on the ionic conductivity of ceramic materials (Bhoga and Singh, 2007; Park et al., 2009). This technology has been used for many years in cars for combustion control (lambda probe). At present, only yttrium oxide-doped zirconium dioxide (Zirconia, YDZ) is used in commercial sensors as a conducting solid-state electrolyte. Conductivity in YDZ requires high temperatures. Therefore, the transducer is heated by an electrical resistance to reach an operational temperature of about 650°C (1202°F). Typical O_2 sensors used in cars are not applicable to rebreathers, mainly because of power consumption and size as they require a reference chamber. In automotive applications, ambient air is taken as the reference, which is, of course, impossible for an underwater breathing apparatus. Micromanufacturing allows miniaturization of such sensors. An overview of micro solid-state gas sensors can be found elsewhere (Dubbe, 2003). A suitable ionic conductor for a CO_2 transducer is sodium super-ionic conductor (NASICON).

A rebreather sensor module has been developed with solid-state sensors for PO_2 and PCO_2 (Sieber et al., 2011). Each sensor is a 2.5x2.5 mm² aluminum oxide substrate on which heaters, electrodes, and solid electrolyte layers are screen-printed using thick film technology. The sensors are heated to 650°C (1202°F) for PO_2 measurement and to 550°C (102°F) for PCO_2 measurement requiring a typical heating power of 1.7 W. If the gas contains He, higher power is needed. Figure 6 shows a sensor module with an 8-bit microcontroller with two heating controls. The sensor signals are digitized by an internal 12-bit A-to-D converter. The module can be connected to a rebreather via I2C or serial USART communication.

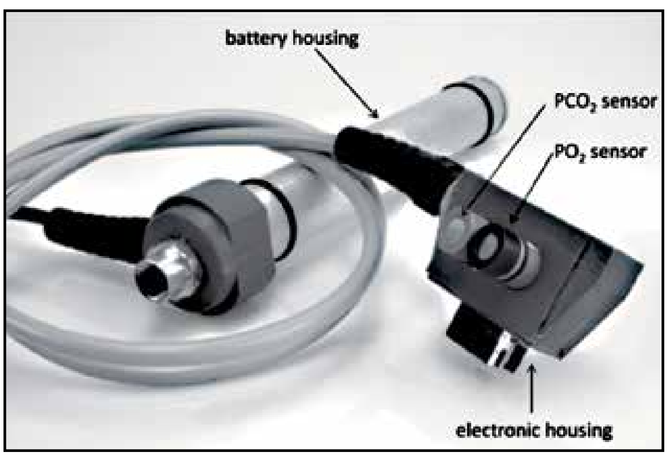

Figure 6. Solid-state sensor module with battery supply. Reprinted with permission of Diving and Hyperbaric Medicine *(Sieber et al., 2011).*

The rebreather sensor module was mounted on a commercially available mouthpiece (MK6 discovery, Poseidon Sweden; Figure 7). The results of the first experiments are shown in Figure 8, and breath-by-breath results appear in Figure 9. The sensors have an exceptionally fast response time of 90-110 ms and linear behavior up to approximately 1.0 bar PO_2. Above this, however, it becomes strongly nonlinear, however, as the sensor is based on a non-consuming technology, the sensor has a nearly indefinite lifetime with no change in calibration over time, thus compensation for non-linearity is possible. Initial trials indicate a reduced output signal in He mixtures, so further research and development is needed.

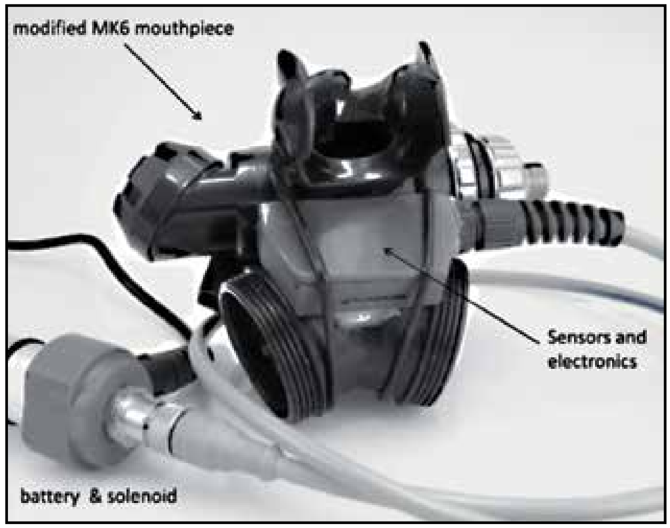

Figure 7. Modified rebreather mouthpiece with solid-state O_2 and CO_2 sensors. Reprinted with permission of Diving and Hyperbaric Medicine *(Sieber et al., 2011).*

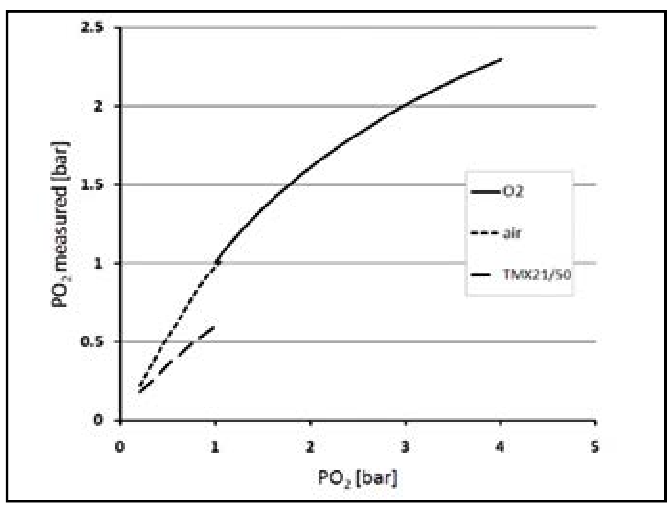

Figure 8. Characterization of the solid-state PO_2 sensors. Reprinted with permission of Diving and Hyperbaric Medicine *(Sieber et al., 2011).*

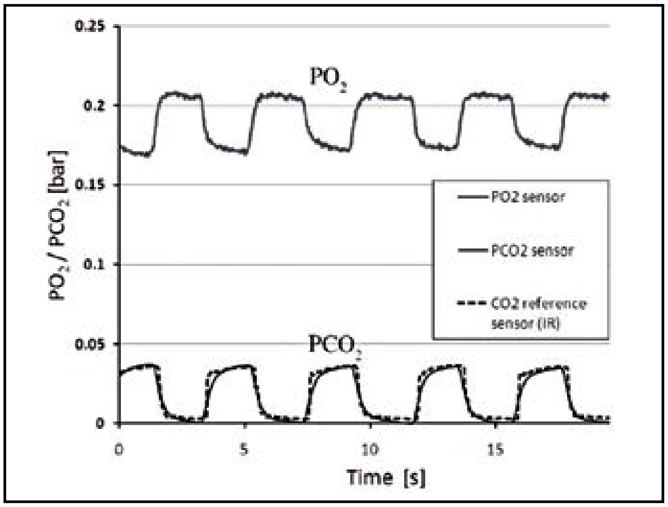

Figure 9: Sample breath-by-breath recording of PO_2 and PCO_2 from the transducer module in the rebreather mouthpiece. Reprinted with permission of Diving and Hyperbaric Medicine *(Sieber et al., 2011).*

CONCLUSION

Most CCR divers today are advanced and/or technical divers with many years of experience. To be able to handle and detect malfunctions safely, a rebreather diver must understand the technical aspects of the system and undergo continuous training. Predive checks by testing cells in a pressure pot or checks during diving by flushing the loop with O_2 to validate sensor function can be performed by a highly trained diver, but it is unlikely that a typical recreational diver with fewer than 15 dives per year could perform these tasks without endangering proper system function.

It should not be necessary for a recreational diver to understand sensor technology in detail to be able to operate a rebreather safely, thus automatic solutions are required. Rebreather electronics must be foolproof and automatically perform sensor checks and validation with warnings in the event of error. As in the automotive industry, advances in electronics and sensor technologies will increase safety.

New sensor technology is also required especially if the recast of the Restriction of Hazardous Substances (RoHS) directive goes into force. This recast now will address also medical consumables and PO_2 sensors with an anode from Pb could be banned from entering the market. This would lead to another shortage of PO_2 sensors and in the worst case could destroy the rebreather industry.

ACKNOWLEDGMENTS

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KMS Prinz Eugen, *Kwajalein Atoll, Marshall Islands. Photo by Andrew Fock.*

PO_2 SENSOR REDUNDANCY

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ABSTRACT

The conventional wisdom that multiple PO_2 sensors lead to an increase in PO_2 measurement reliability is examined in the light of voting algorithms and statistical dependence between the sensors. An alternative paradigm relying upon PO_2 sensor validation is discussed.

Keywords: asymmetrical outcomes, redundant systems, sensor validation, statistical dependence, voting algorithms.

INTRODUCTION

The galvanic PO_2 sensors in a rebreather are the starting point for the rebreather keeping the loop PO_2 within the desired operating bounds. If the PO_2 sensors fail, then the diver can die without warning. Thus, the reliability of the PO_2 measurement is fundamental to the safety of the rebreather diver. To this end, most rebreathers incorporate three or more PO_2 sensors in a voting system configuration. The rationale for doing so is the perception that multiple PO_2 sensors lead to improved reliability. In this paper I examine the basis for this claim and offer an alternative paradigm based upon sensor validation.

RELIABILITY

In the following discussion I frequently use the term "PO_2 sensor failure." It is my experience that most people think of a sensor/system failure as a catastrophic failure — for example, a PO_2 sensor that reads zero regardless of the actual PO_2. In my opinion, this is the wrong way to think about failure. Rather, I consider a sensor to have failed if it reads wrong enough for long enough such that it has an impact on the safety of a diver. As well as being more useful, I think this definition also comports more closely with the actual failure modes experienced with galvanic PO_2 sensors

Reliability of a single measurement system

Before delving into redundant measurement systems, it is instructive to examine a single (i.e., non-redundant) measurement system.

PO_2 measurement is a system consisting of the following components:

- PO_2 sensor
- Connectors and cables
- Amplifiers and their attendant electronics
- Analog/digital converter
- Firmware
- Calibration gas

The probability of the overall measurement system working (ps) is the product of the probability of its constituent components working. Thus:

$p_s = \Pi p_c$, where p_c is the probability of each component working. (Equation 1)

From this, it should be appreciated that $p_s < p_{cmin}$, where p_{cmin} is the probability of the least reliable component working. While most people instinctively understand that one should concentrate on improving the least reliable component in the system, it is my experience that most are not aware of just how dramatically the system is dominated by the least reliable component. To illustrate this, consider a hypothetical system that consists of four components, as shown in Table 1.

Table 1.

	Comp #1	Comp #2	Comp #3	Comp #4	Overall system
P(working)	0.995	0.997	0.998	0.999	0.9890
Failures per 1,000 trials	5	3	2	1	11

As well as listing the probability of working, the table lists the data in its equivalent format of failures per 1,000 trials. Now let us assume that we can improve the reliability of any one component by an order of magnitude. What happens if we do this to the least reliable component? Table 2 now looks like this:

Table 2.

	Comp #1	Comp #2	Comp #3	Comp #4	Overall system
P(success)	0.9995	0.997	0.998	0.999	0.9935
Failures per 1,000 trials	0.5	3	2	1	6.5

This represents an improvement in the overall system of (11 – 6.5) / 11 = 40.9 percent. It is sobering to note that improving the reliability of the worst component by an order of magnitude in this case produced only a 40.9 percent improvement in overall system reliability. However, if you think that is bad, consider what happens if we improve the best component by an order of magnitude in Table 3:

Table 3.

	Comp #1	Comp #2	Comp #3	Comp #4	Overall system
P(success)	0.995	0.997	0.998	0.9999	0.9899
Failures per 1,000 trials	5	3	2	0.1	10.06

In this case the overall system reliability has been improved by a paltry (11 – 10.06) / 10.06 = 9 percent.

Thus the bottom line is that in working to improve the reliability of the PO_2 measurement system it is crucial that we concentrate on the least reliable components. In my opinion, this means the PO_2 sensor itself and the correctness of the calibration gas.

Reliability of a redundant system

What should be clear from the example of a single system is that significantly improving its reliability is very hard. An alternative paradigm is to resort to redundancy. The basic concept is well understood. Rather than trying to improve the reliability of the least reliable component (the PO_2 sensor itself), instead use multiple sensors in parallel. Qualitatively, such a system is "obviously" more reliable. The question is, just how much more reliable is such a system?

We can answer this question via a probability tree. The nominal probability tree for a three-sensor system appears in Figure 1.

In this tree, S1, S2 and S3 refer to oxygen sensors 1, 2 and 3. P(Bad) = q is the probability that the sensor has failed. Conversely, P(Good) = p is the probability that a sensor has not failed, where p + q = 1. If we examine the branches of this tree, it is apparent that there is only one path that leads to total system failure — namely the one on the left-hand side. This is illustrated in Figure 2, where the failure path is in red, and all other (non-failure) paths are in green.

The probability of taking the red path is the product of the three probabilities, thus:

$$P(\text{failure}) = q * q * q = q^3. \qquad \text{(Equation 2)}$$

Table 4 puts some numbers on this for various values of q.

Table 4.

Single sensor p(failure) = q	Failures/ 10^6	Three sensor p(failure)=q^3	Failures / 10^6	Improvement
0.01	10,000	0.000001	1	10,000
0.005	5,000	0.000000125	0.125	40,000
0.001	1,000	0.000000001	0.001	1,000,000

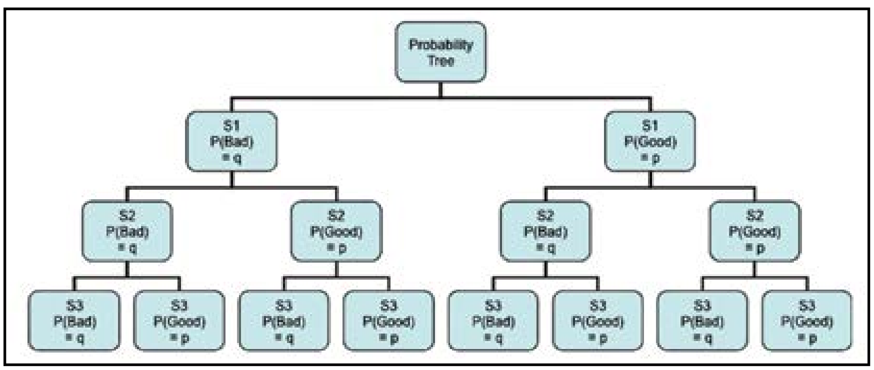

Figure 1.

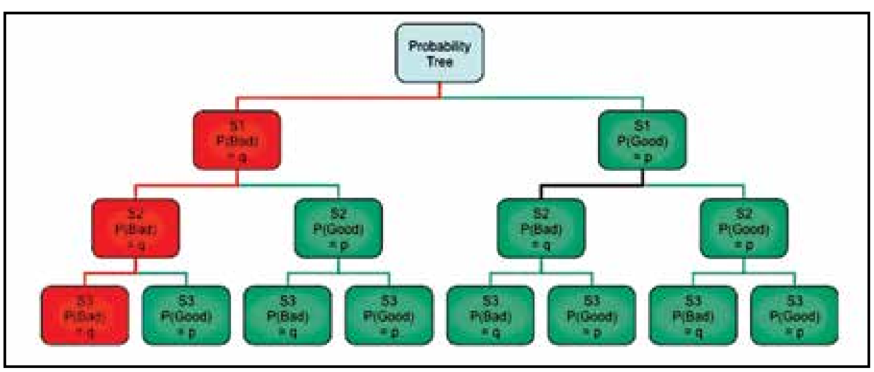

Figure 2.

There are two things that are apparent from this table:

1. The astonishing level of improvement that redundancy appears to bring.
2. Redundancy disproportionately improves already very reliable systems.

The effect of voting

The above analysis is overly simplistic in that it assumes that sensors are either good or bad. Clearly if a sensor is reading zero, then it is bad. However, if a sensor has a non-zero reading, then without additional information it is impossible to tell whether it is good or bad. It is for this reason that most rebreathers resort to voting logic. In this paradigm:

1. If all three sensors agree within some tolerance, then they are all deemed good.
2. If two of the sensors agree within some tolerance, and the third disagrees with them, then the first two are deemed good, and the third is deemed bad.
3. If none of the sensors agree within some tolerance, then they are all deemed bad.

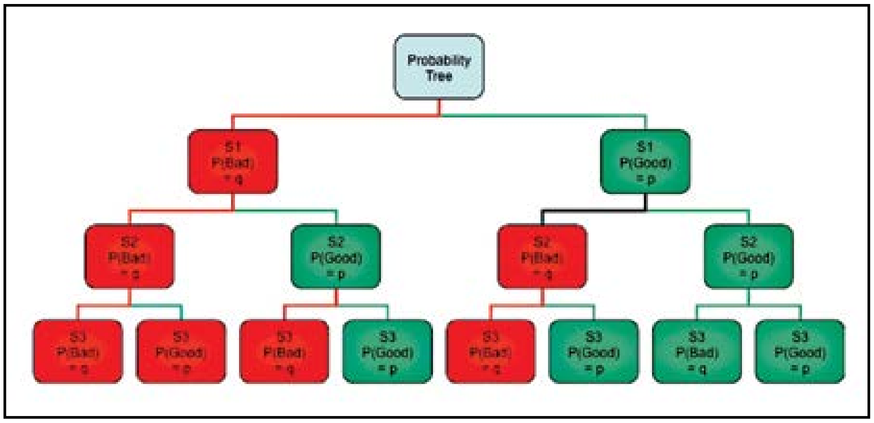

Figure 3.

The question is, how does this voting paradigm affect the overall reliability of the system? We can determine this by looking at the probability tree again. The tree in Figure 3 shows the good paths in green and the bad in red. For a path to be good, at least two sensors have to be good.

Working from left to right across the diagram we can see that the probability of failure is

$$P(\text{failure}) = q{*}q{*}q + q{*}q{*}p + q{*}p{*}q + p{*}q{*}q = q^3 + 3q^2p. \quad \text{(Equation 3)}$$

If we replace p with (1-q), then

$$P(\text{failure}) = q^3 + 3q^2(1-q) = 3q^2 - 2q^3 = q^2(3 - 2q) \quad \text{(Equation 4)}$$

If we now repeat the exercise of computing the improvement in reliability, then we get the numbers shown in Table 5.

Table 5. Effect of voting logic.

q	Failures / 10^6	$q^2(3 - 2q)$	Failures / 10^6	Improvement
0.01	10,000	0.000298	298	33.5
0.005	5,000	0.00007475	74.75	66.9
0.001	1,000	0.000002998	3	333.5

If we compare Tables 4 and 5, rather than getting four, five or six orders of magnitude improvement in reliability in the true doubly redundant system, we are instead getting only one to two orders of magnitude improvement in reliability once we start using voting logic. If this were the only issue, then this would likely be acceptable. However, as will now be shown, the situation is far worse even than this.

The effect of statistical dependence

The above analysis makes the explicit assumption that all three oxygen sensors are statistically independent. What does this mean?

"In probability theory, to say that two events are independent intuitively means that the occurrence of one event makes it neither more nor less probable that the other occurs." (http://en.wikipedia.org/wiki/Independence_%28probability_theory%29)

In a rebreather, the "event" that we are concerned with is the measurement system providing the wrong PO_2 value. A little bit of thought shows that achieving statistical independence of the PO_2 measurements is stunningly difficult. Examples of things that make the PO_2 sensor readings statistically *dependent* include:

- Common calibration gas
- Sensors from the same manufacturing lot
- Sensors that have been exposed to the same PO_2/time/temperature profile
- Common environment, particularly with regards to temperature and relative humidity
- Common measurement systems
- Common firmware for processing the signals

Common calibration gas

If all three sensors are exposed to the same and wrong calibration gas, then clearly they will all read incorrectly. Indeed it would not matter how many PO_2 sensors a rebreather contained in this situation. Thus if a common calibration gas is used, then all statistical independence is lost; more important, if an incorrect common calibration gas is used, the probability of failure is 1.

Sensors from the same manufacturing lot

If all three PO_2 sensors come from the same manufacturing lot, then any defect in that lot will likely be common to all three sensors and thus could lead to all three sensors failing in a similar manner. In which case the sensors are not statistically independent.

Common profile

The failure rate of PO_2 sensors is believed to be a function of a sensor's PO_2 exposure, the time of the exposure and temperature at the exposure. If all of the sensors have been exposed to the same use profile, then once again the sensors are not statistically independent.

Common environment

A known failure mode for the PO_2 sensors is for them to become coated in condensate, preventing the loop gas from being sensed. If conditions in the breathing loop are such that condensate is forming, then it is highly likely to be forming on all sensors — and thus they will all stop responding. Once again, the sensors are not statistically independent.

Common measurement hardware

In most rebreather designs, the multiple oxygen sensors are fed into common hardware. For example, the sensor signals are bundled into a common cable that connects via a common connector to a common printed circuit board. The signals are then amplified using a common amplifier and the amplified signal sent to a common analog-digital converter using a common voltage reference. (Each PO_2 signal has its own amplifier. However, all the amplifiers are in the same integrated circuit.) Failure of any of these components will likely cause all three sensor readings to be invalid and statistical independence to be lost.

Common firmware

The output of the analog-digital converter is then processed by firmware. This firmware is nearly always common to all sensors, and thus a defect (bug) in the firmware can easily equally affect all three readings, once again causing statistical independence to be lost.

Clearly, the designers of rebreathers can take steps to mitigate some of these factors, and the users of rebreathers can take steps to mitigate other factors. However, at the end of the day common sense tells us, and real-world experience confirms, that multiple PO_2 readings are at best only approximately statistically independent. The question is, what is the impact of this statistical dependence on the overall measurement reliability? This problem is usually solved using Bayesian statistics; however, it can be handled perfectly adequately using a probability tree.

Analysis

To understand the effect of statistical dependence, let us start off by considering the probability tree for two sensors as in Figure 4.

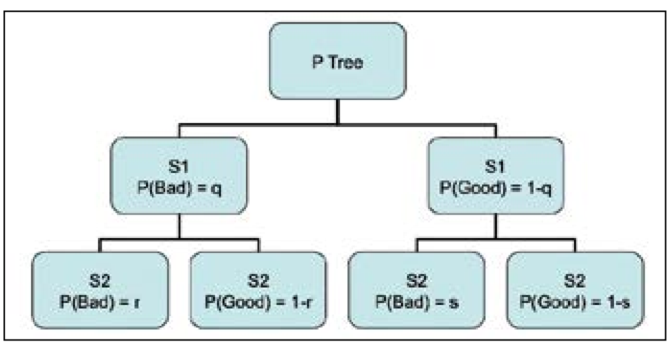

Figure 4.

For the first sensor S1, the probability of it being bad is q as before. For the second sensor, if it is statistically independent of S1, then its probability of being bad is also q. Thus r = q and

P(both sensors bad when they are completely independent) = $q * q = q^2$. (Equation 5)

However, if the second sensor is statistically dependent on S1 to some degree, then its probability of being bad is higher if S1 is bad and is lower if S1 is good. Thus in Figure 4, $r \geq q \geq s$ and:

P(both sensors bad when there is some statistical dependence) = qr. (Equation 6)

If two sensors are completely statistically dependent, then if the first sensor is good, the second sensor is guaranteed to be good; if the first sensor is bad, then the second sensor is guaranteed to be bad. Thus in the limit of complete statistical independence, r = 1 and s = 0. In this case:

P(both sensors bad when there is complete statistical dependence) = $qr = q * 1 = q$. (Equation 7)

From Equations 5 and 7 we get the result that for two sensors that have some degree of statistical dependence:

$q \geq$ P(Both sensors failed) $\geq q^2$ (Equation 8)

To put this into plain English, when two oxygen sensors have some degree of statistical dependence, the probability of both failing is somewhere between q and q^2, with the best case being q^2 and the worst case being q. The worst case, of course, is equivalent to a single sensor.

Now let us turn our attention to a three-sensor configuration. I am going to assume that S1 and S2 have some degree of statistical dependence and that S3 is statistically independent, such that its probability of failure is q regardless of what happens to S1 or S2.The probability tree now appears as in Figure 5.

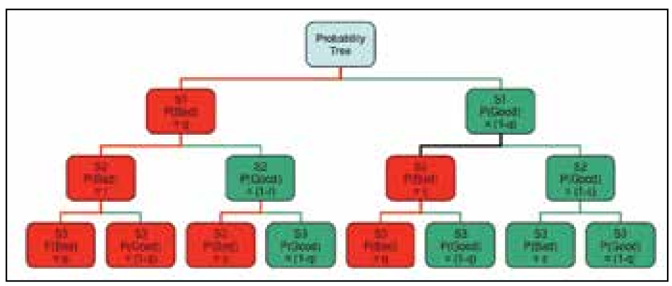

Figure 5.

As before, we apply voting logic and sum the paths that lead to a red box at the S3 level. If we do this, we compute the probability of failure as:

P(2 out of 3 failed) = $qrq + qr(1-q) + q(1-r)q + (1-q)sq$ (Equation 9)

This can be simplified to:

P(2 out of 3 failed) = $q(r + s) + q^2(1 - r - s)$ (Equation 10)

For a statistically independent system q = r = s, and Equation 10 becomes:

P(2 out of 3 failed) = $q(q + q) + q^2(1 - q - q) = q^2(3-2q)$ (Equation 11)

Note that Equation 11 is the same as Equation 4.

For a system where S1 and S2 are completely statistically dependent, then r = 1, s = 0 and Equation 10 becomes:

$$P(\text{2 out of 3 failed}) = q(1 + 0) + q^2(1 - 1 - 0) = q$$

(Equation 12)

Combining Equations 11 and 12 we have:

$$q \geq P(\text{2 out of 3 failed}) \geq q^2(3\text{-}2q)$$

(Equation 13)

Equation 13 is a remarkable result. It tells us that in a two out of three voting system, the best possible result is $q^2(3\text{-}2q)$ when all the sensors are completely independent, and the worst possible result is q, that is, the same as a single sensor. To achieve the worst result it is only necessary that two of the sensors are completely statistically dependent. Obviously where any given rebreather lies between the limits of Equation 13 is debatable. However, as shown above, there is a huge amount of statistical dependence in a typical rebreather, and hence anyone who thinks he is operating firmly toward the $q^2(3\text{-}2q)$ end of the line is deluding himself. Furthermore, it is essential that divers understand the worst-case performance of their PO_2 measuring system. I suspect that most would be stunned to realize that in the limit they are diving with a single oxygen sensor.

Implications of asymmetrical outcomes

There is one last factor to be introduced concerning voting algorithms and statistical dependence. Consider a system where the three PO_2 sensors are reading 0.4, 1.0 and 1.2 bar respectively and the setpoint is 1.0. What value should the voting system return as the PO_2? The obvious answer (and the answer selected by the vast majority of the RF3 audience) is to reject the 0.4 reading, and average the other two sensors together to give a PO_2 value of 1.1 bar. The interesting questions are, what does the rebreather do with this data, and how should this factor into the voting logic decision? The two main uses for this PO_2 reading are:

1. Decide whether to inject oxygen.
2. Update the tissue tensions

With this information, let us consider the possibilities.

In Table 6, clearly the first two entries are benign in that in both cases the system will work to keep the loop breathable and the diver from getting bent. It is the third and fourth entries that are problematic. In the third case, the wrong decision leads to eventual hypoxia and incorrect tissue tensions possibly leading to decompression sickness (DCS). In the fourth case, the wrong decision leads to eventual hyperoxia and incorrect but conservative tissue tensions, with minimal risk of DCS. Now, it is well known that many divers can withstand hyperoxic environments for long periods. However, I know of no divers that can withstand hypoxic environments. Thus in a situation where one is not sure whether to add gas (and risk hyperoxia) or not add gas (and risk hypoxia and DCS), the best decision is to add gas. (We must differentiate between the best decision and the correct decision. Clearly the best decision could be incorrect.)

So how does this play into the issue of statistical dependence? Well, the numbers cited above are actually numbers from a dive conducted by Dr. Richard Pyle on a Cis-Lunar MK5 a number of years ago. It turned out that 0.4 was the correct reading and the other two sensors had simultaneously failed via condensate locking the sensors (thus the sensors were not statistically independent because they were in the same environment). The MK5 was faithfully voting out the 0.4 reading, and, if not for some smart thinking by Dr. Pyle, would have likely driven the loop into a hypoxic state.

The implication for voting logic is this: Since sensor dependence is unavoidable, it is riskier to vote out a sensor reading that is too low than it is to vote out a sensor reading that is too high. Failure to take into account this asymmetry in outcomes will result in a further decrease in system reliability beyond those postulated in Equation 13.

Table 6. Asymmetric possibilities.

Selected PO_2	Actual PO_2	Implications
1.1	1.1	No gas injection. Loop remains breathable. Tissues tensions updated correctly
0.4	0.4	Gas injection. Loop remains breathable. Tissue tensions updated correctly.
1.1	0.4	No gas injection. Loop will eventually become hypoxic. Tissue tensions are being incorrectly updated.
0.4	1.1	Gas injection. Loop will eventually become hyperoxic. Tissue tensions are being incorrectly but conservatively updated.

Practical recommendations

In the second half of this paper I present an alternative paradigm to sensor voting. However, if you already own a rebreather that uses two out of three voting, here are some practical steps that you can take to push your probability to the $q^2(3\text{-}2q)$ end of the line.

1. All three sensors should come from different manufacturing lots or manufacturers. (In some cases, manufacturers recommend/require that you use a particular sensor, in which case you will have to evaluate the risk of a defect common to the cell manufacturer vs. going against the rebreather manufacturer's recommendation. It is not an easy decision.)

2. Stagger when you change sensors. For example, if you change sensors every six months, switch to a schedule whereby you change one sensor every two months and stick to it. Do not be tempted to keep a sensor that is still good in case you end up using it later and destroying your statistical independence.
3. Check, double check and triple check your calibration gas. Apropos of this, see if your rig will detect a bad calibration gas. For example, will it flag an error if instead of using pure O_2 to calibrate the sensors you inadvertently use nitrox 36? If the rig does not flag an error, I would:
   a. Demand that the manufacturer add logic to catch such an obvious mistake, and
   b. Quadruple check the calibration gas.
4. Purchase an independent PO_2 measuring system that you can install elsewhere in the loop. However, when doing so, avoid shooting yourself in the foot by:
   a. Making sure it comes from a different vendor such that the electronics and its attendant software really are different from what you have in your rig.
   b. Ensure it uses a PO_2 sensor from a different manufacturer than what you are using in your rig. If this is not possible, make sure that it is from a different manufacturing lot.
   c. Calibrate it independently of your rig, preferably using a different gas source.
5. If you find yourself underwater and the voting logic is voting out a low sensor reading, then remember that statistical dependence could be coming into play and that you should consider the fact that it is better to add O_2 and risk hyperoxia than it is to not add O_2 and risk hypoxia.

Finally, I must comment on a paradigm I have seen used a lot. Many divers seem to be at least vaguely aware of the problem of statistical independence. As a result, they will take steps to make sure that one of their sensors is different from the other two, reasoning that this gives them the desired variability. As I hope I have illustrated here, it does no such thing. All it requires is for two of the sensors to be operating dependently and the voting logic will ignore the "independent" sensor. All three sensors must be independent!

An alternative paradigm

At its heart, the fundamental reason that voting algorithms are used is because we simply do not know which of the sensors (if any) are actually working correctly. Instead we reason that by having multiple sensors and using voting we increase the probability that we are getting a correct reading. Well, as I hope the above discussion has shown, this is a rather dubious assumption when one takes into account statistical dependence.

This obviously begs the question whether there is an alternative paradigm to using three sensors in a voting configuration. Well, there is. In the Poseidon series of rebreathers we have taken a fundamentally different approach. The idea is as follows.

Have a primary PO_2 sensor that is placed in the breathing loop in such a way that diluent and/or oxygen may be blown directly across the PO_2 sensor at any time before, during or indeed after the dive. With this capability and knowing the fraction of oxygen (FO_2) in the diluent and oxygen supplies, together with the depth, it is possible to validate that the primary oxygen sensor is indeed working properly. The validation gas used depends, of course, on the depth, with O_2 being used in shallow water and diluent used in deeper water.

The expected reading of the O_2 sensor is thus: $FO_2 \cdot$ absolute pressure.

For example, consider a diver at 20 m (66 ft) using air as a diluent. The FO_2 of air is 0.21, and thus the expected PO_2 reading of the sensor is $0.21 \cdot (20/10 + 1) = 0.63$ bar. If when the sensor is exposed to diluent at 20 m (66 ft) it reads 0.63 bar ± some tolerance, then the system can have high confidence that the sensor is indeed working correctly. (The actual algorithm used by the Poseidon rebreathers is considerably more sophisticated than this. Suffice it to say that here I am just illustrating the fundamental principles at work.)

Actually, the previous statement was overly simplistic. If the PO_2 sensor does read the expected value, then it is more accurate to say that the PO_2 sensor, the depth sensor and assumed gas FO_2 are consistent. To put it another way, if the PO_2 sensor reads the wrong value, then all of the following are possible:

1. The PO_2 sensor is bad.
2. The depth sensor is bad.
3. The wrong gas is being used.
4. Any combination of the above.

Thus the act of exposing the PO_2 sensor to an assumed gas at an assumed depth simultaneously validates three things that can kill a rebreather diver: a bad PO_2 sensor, a bad depth sensor or the wrong gas. That is a very powerful test.

In this paradigm, it is thus possible to know with a very high degree of certainty whether the primary PO_2 sensor is indeed good or bad. An obvious question is what happens if you determine the sensor is bad? Well, in Poseidon's case there is a second PO_2 sensor. This is, for the most part, simply a backup sensor. (Again I am oversimplifying, in part, not to obscure the point and, in part, to protect Poseidon's intellectual property.) If the primary sensor validation algorithm suggests that the primary sensor is not to be trusted, then the diver will be told to abort the dive. (If you think aborting the dive just because one sensor has failed is unnecessary, then I clearly have not gotten through to you the problem of statistical dependence on your three-sensor rig.) The preferred dive-abort scenario is, of course, an open-circuit abort. Where this either is not practical or the diver chooses to override the alarm system recommendation and stays in closed-circuit, then in this case we will use the secondary sensor to control the loop PO_2. Note that the previous discussion of statistical dependence applies equally here, and thus if the diver hasn't taken steps to ensure the two sensors are independent, then once again he has done himself a major disservice.

It is instructive to compare the failure scenarios for the two paradigms.

For the voting case, you know that two sensors agree and one does not, and thus something is wrong. What you do not know for sure is which is correct, if either. It is more likely that the two sensors that agree are correct, but it is not guaranteed. It is also possible that they are all wrong. What to do is not obvious.

For the validation case, you know the primary sensor is bad. Your choice now comes down to whether to trust the secondary sensor or not.

Given the above two scenarios, I prefer the choice offered by the validation scenario.

Hyperoxic linearity

The ability to validate the primary PO_2 sensor also confers another crucial benefit, which at Poseidon is referred to as the hyperoxic linearity test (HLT).

Figure 6 shows a typical PO_2 calibration curve, showing calibration points of 0.21 and 1 bar, corresponding to air and pure oxygen at 1.0 atmosphere. Also shown in Figure 6 is the normal operating point for a rebreather, around 1.3 bar. As the red

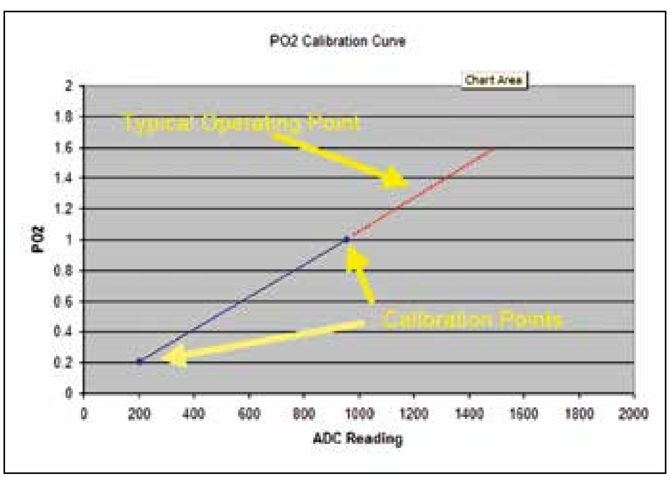

Figure 6.

dotted line shows, the rebreather is being operated at a point well above its highest calibration point. In most cases it is an article of faith that the PO_2 sensors are indeed linear up to the operating point and that they do not operate something like as shown in Figure 7.

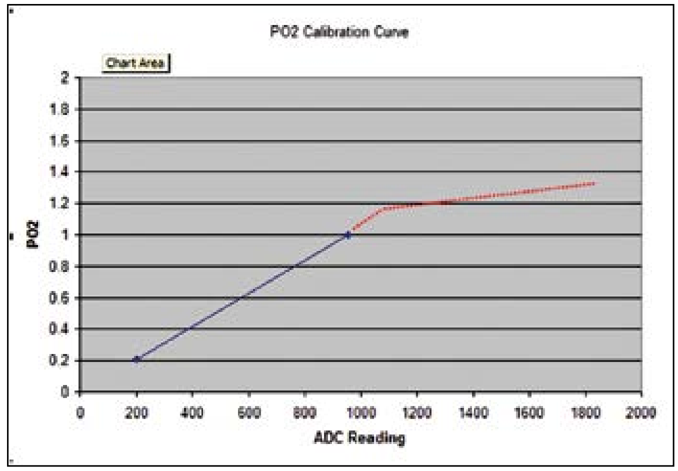

Figure 7.

Indeed, the only reason that rebreather divers feel they can get away with this assumption is because they reason that if a sensor is not linear it will show up in the voting logic. If the voting logic is not anywhere near as reliable as postulated in this paper, then I would also suggest that the assumptions about hyperoxic non-linearity being caught are equally fraught with danger.

In Poseidon's case, with the ability to inject oxygen directly across the PO_2 sensor during the dive, Poseidon rebreathers do the following.

As the diver descends past about 6 m (20 ft), the rebreather injects pure oxygen across the PO_2 sensor and looks at its behavior. If the sensor does indeed read as expected, then the sensor is indeed linear into the hyperoxic region, and it is reasonable to operate at a setpoint above the highest calibration point.

SUMMARY

Unless very careful steps are taken by both the manufacturer and the diver, three PO_2 sensors in a voting configuration can have a reliability little better than a single sensor. An alternative paradigm using active sensor validation during the dive offers multiple benefits including:

- True automatic sensor calibration and gas validation.
- Proof that the O_2 sensor reading, depth sensor reading and gas mix are consistent.
- Proof that the O_2 sensor can operate correctly in the hyperoxic region.

ACKNOWLEDGMENTS

I thank Poseidon for providing financial support; Dr. Richard Pyle for being a terrific sounding board and a fabulous test diver such that the concepts herein saw the light of day; and Dr. William Stone for demonstrating that there are no insurmountable problems.

PUBLIC DISCUSSION

LEON SCAMMERHORN: At InnerSpace Systems, we have designed products for quite a while in-house. Since we built the rebreather, we have tried to teach people how to use millivolts. You have a system monitor page that you can lock open and the diver can monitor in real time. You have the fluctuation of raw data coming straight from the sensors that is not affected by calibration. A diver can read the raw data in real time and determine if two sensors are drifting off and the low one is correct. We have seen this happen. It depends on the divers themselves; they have to be the voting logic. I have peeled apart a rebreather at 215 ft (66 m) with one sensor, the solenoid off, a partially flooded loop, and handsets cut off. If there is one sensor working, the diver can still survive and finish decompression. It depends on a well-designed rebreather and quality oxygen sensors. However, frivolous lawsuits caused the best sensor manufacturer to leave the rebreather business and reduced the overall safety of the industry. The problem Nigel described seemed similar to problems in manufacturing and reliability, which means I should have two independent scrubber loops because CO_2 absorbent has the same issues.

UNIDENTIFIED SPEAKER: This seems like a really important subject. I do not quite understand the millivolts issue. Is Leon suggesting that if you have millivolts information, this solves this problem? I would like to hear this discussed.

JOHN CLARKE: I do not think millivolts will solve it. The important point is not that one manufacturer is using a preferred method over another. The interesting point is that the topic of non-independence is relatively new in diving and is something that I would like to think about. I always assumed we have independence of the three sensors. Clearly, that is wrong.

UNIDENTIFIED SPEAKER: Leon and I have had this discussion before. My opinion, not stated as clearly as Nigel presented, is that millivolt data and the calibration data are the same as long as the calibration is correct, which we do not necessarily know, and also requires a working computer. Reading the original raw millivolts does not solve the problem if the system gets wet. The PO_2 and the millivolt readings will still agree although both are wrong. This seems more complicated than just looking at the raw millivolt data or PO_2.

UNIDENTIFIED SPEAKER: Why do people drown — three Red Bulls, lack of sleep, a bit of a cold, a fever, a temperature, CO_2 retention, Viagra? All these issues might make a healthy, experienced rebreather diver susceptible and make it difficult for him to monitor his instruments. The issues include what is measured, what the diver sees, and how he interprets the data.

MICHAEL MENDUNO: This seems really important. Someone please explain the millivolt thing for those of us who do not understand. How does this address the problem of independence and redundancy? We need to understand so we can contrast the two approaches. This is the core of the issue. If you cannot see what is there, if your eyes are not working, it is really problematic. I propose that we take the time to talk about this in detail and not pass it over. It seems what safety is about.

CLARKE: Many topics need to be explored this afternoon. If we cannot solve this one within the next few minutes, which I doubt we can, we should explore it later. I am not an expert, but I have seen a diver who almost died because of voting logic errors. The question is if there were no voting logic, would that resolve the independence problem? Perhaps Leon can say that a little more succinctly.

SIMON MITCHELL: Leon, please repeat what you said. It was really important.

SCAMMERHORN: InnerSpace Systems and other manufacturers display the sensor data in millivolts. If the voting logic is well-designed, the system would work with two bad sensors while the third one is also going bad. If what you are breathing is in question, you can go into the system monitor page and see the millivolts values coming directly from the sensors. If the diver is trained to do simple math, if the millivolt and calibrated sensor readings are truly independent of each other, and if they agree, you should not necessarily trust that. If I look at the system monitor page and see that one sensor is going bad while the other is still working, I think I have enough data to determine whether to stay on the loop with a single sensor or bail out. This is why we make the millivolt readings easily accessible and teach divers to do simple math. Two systems made by different manufacturers are independent. This is good if you are at 330 ft (100 m).

For example, add a Shearwater monitor to an InnerSpace unit, and you have two different manufacturers reading three independent sensors. That gives the diver enough data to determine what he or she is breathing. Two sensors are independent, but I think a good rebreather and good diver should be able to function with only one sensor. If I physically disconnect two of three sensors, the rebreather will still function, and I should not have to worry about voting logic to tell the solenoid when to add oxygen. It is a good idea to squirt diluent over the sensors if you have the right oxygen fraction and a working depth sensor, but that adds another failure point, and you want to minimize the number of failure points. I argue that this is really about sensor manufacturing reliability. It is a quality-assurance issue. By analogy, I should have a separate scrubber canister to ensure redundancy. I believe the central issues are material and manufacturing quality.

NIGEL JONES: Let me try to summarize what you are saying, Leon. Here are the points I got. Number one is that millivolt readings are better than PO_2 readings.

SCAMMERHORN: If the PO_2 readings are calibrated.

JONES: Point number two was you have independent systems such as an additional Shearwater system in the loop. Your third point was why not have redundant scrubbers, etc.? Did I miss anything?

SCAMMERHORN: No.

JONES: Let us talk about millivolt readings first. Galvanic oxygen sensors generate current, which flows through a resister and develops a voltage. That voltage is read by the electronics and converted into an oxygen partial pressure reading. In general, oxygen sensors are considered linear — that is, there is a linear relationship between the millivolt readings and the oxygen sensor readings you see on your display. As such, they are the same. Now, here is where it gets interesting. If the PO_2 reading is bad, it is because the millivolt reading is bad unless you have a software problem. I recounted the story of how Richard Pyle found three disparate oxygen sensor readings. How did he determine that he had a serious problem? As you described, he looked at the millivolt readings and could see that the low sensor reading was fluctuating in the manner he would expect, but the other two were not. That was the key. But to say that the millivolt readings per se are statistically independent is wrong. They are not because the oxygen sensors themselves are statistically dependent. I agree that having a millivolt page is useful if you can train divers to look at it and understand the normal variation. But the real problem is that a task-loaded diver will rely on the computer to make the right decision. If he or she checks the instruments every minute or two, that is great; but if not, oh dear, there is a problem. That is point number one.

Point number two was the independent Shearwater system. I think that is a good idea. You cannot get much more statistically independent than having a totally independent system that you calibrate separately. I am not sure if that was your point or not, but it is a great way of achieving statistical independence. Your third point was why we do not have redundant canisters, etc.? In my humble opinion, the oxygen sensors are the least reliable components in a rebreather, but more practically, a rebreather with two or three canisters is not diveable. We know that because we have built them, and they are monsters. If you are doing extreme diving, they may be justified, but for a typical dive, they are not practical. Kevin Gurr spoke extensively about CO_2 monitoring yesterday. The bottom line was that one of the leading causes of rebreather deaths seemed to be failure to properly pack the scrubber. But even then, you have a statistical dependence problem. If I put two canisters on a rebreather and the same diver packs both canisters, if he screws up on one, he is probably going to screw up the other as well. You need one prepacked canister and one packed by me to achieve statistical independence.

SCAMMERHORN: I argue that the most unreliable component on the rebreather is the diver.

MENDUNO: Are you saying if you have millivolt information, you are more likely to be able to resolve sensor problems as Rich did?

JONES: Well, possibly, if the right data are available. Say you have a sensor alarm at 100 m (330 ft), and when you check your PO_2 readings you see disparate values. So you switch to the millivolt page and do the mental arithmetic to estimate the PO_2 that each sensor is indicating. This is what Rich did on his Mark V dive, and we incorporated into later Mark V software. Is more information better? Yes, if you understand how to interpret the information. I just realized Leon's other point was that the depth sensor may not be reliable or oxygen fraction in the diluent gas may not be accurately known. I completely agree. That is the whole point about calibrations — everything must be reliable, and the diver must correctly interpret the information presented by the instruments. We are most likely to interpret the problem to be with the O_2 sensor, but it may be with the depth sensor, or we may forget what is in the diluent gas.

MENDUNO: For further clarification, if the sensors are good, the millivolt readings will be linear with the PO_2, and the computer will read the millivolt information and display the PO_2. I am still trying to understand how that solves the problem.

JONES: The oxygen sensors produce a signal in millivolts. That is sampled by an analog-to-digital converter in microseconds, so you are getting a single point in time. Then all sensor signals are filtered and averaged by lots of software before the diver sees the PO_2. As a diver, you have no idea what went on between the sensor measurement and the number in the display, and how this is done differs among manufacturers. The advantage of a well-designed millivolt display is minimal processing: You see the raw data from the analog-to-digital converter with no refinements and less chance of introducing error. There are times, however, when interpreting the display and making the right decision is not obvious.

MENDUNO: Under stress of the situation, you have to interpret the data and decide what to do. Presumably, a diver can do this better than a computer?

JONES: Yes, but it is also helpful that you are looking at unfiltered data. The Mark V, for example, has a redundant oxygen display that is an analog gauge with no software, no processing, no filtering, nothing, just raw signal. That is useful because if you have any doubt about the software, you can bypass the PO_2 display and get a clear picture of what is going on. If the O_2 measurement software crashes, you can bring up the millivolt display. If they are in the appropriate range, good, unless they are not moving, which would indicate there may be a problem. Well-designed software should recognize a static display and set off alarms telling you to abort the dive.

DAVE CONLIN: Is there is a reason to have only one sensor logic algorithm? Would there be advantages to multiple algorithms? If the sensors are reading correctly, would different algorithms give you the same result? In other words, could the algorithms check on each other?

JONES: Good question. Should you have one voting algorithm or multiple voting algorithms? I think multiple algorithms would be good, providing you display all the results and allow the diver to make the decision. But if you take this idea to the limit, you end in the realm of fuzzy logic. The bottom line is that a computer is a GIGO system — garbage in, garbage out. If data going in are bad, it is tough for algorithms to give you a good result.

RICHARD HARRIS: Thank you, Nigel, for reviewing an incredibly important topic. We have had blind faith in three oxygen cells and how they work together. Clearly, this cannot be totally relied upon. My experience using manual rebreathers with three cells that disagree has led me to the conclusion that being able to think through a problem is very important whether with a millivolt or PO_2 display. I suspect Richard Pyle would have made a similar decision with the PO_2 readings instead of the millivolt readings. Extra information is good but probably not necessary most of the time. Perhaps it comes back to training in that training needs to teach the way to manage problems.

Kevin Gurr diving a Sentinel CCR in a cave. Photo by Richie Kohler.

CO_2 MONITORING AND CANISTER LIMITS IN REBREATHERS

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INTRODUCTION

CO_2 safety in rebreather diving is influenced by equipment, physiological, and environmental variables listed in Table 1. The practical mechanisms for coping with these variables and how they affect CO_2 management and diver safety are described below.

Table 1. Variables that affect CO_2 safety in rebreather diving.

Equipment	
	Remaining absorbent life
	Mechanical failure of the CO_2 scrubber
	CO_2 measurement in the inspired and expired gases
	Resistance to gas flow in the breathing loop
Physiological	
	Diver work and ventilation rates
	Resistance to gas flow in the lungs
Environmental	
	Depth and gas mix, which determine gas density
	Water temperature

The CO_2 curve for inspired gas

Figure 1 shows the CO_2 curve in the inspired gas of a rebreather. The curve has three stages. At the start of a dive with a properly filled CO_2 canister, a CO_2 analyzer should read zero millibars (mbar) of CO_2, and predicting the remaining absorbent life is difficult. In the second stage, CO_2 begins a gradual rise, while the rise is rapid in the final third stage. The European Union (EU) and U.S. Navy recognize 5 and 10 mbar as alarm limits toward the end of the canister life at which a diver should consider finishing a dive or coming off the breathing loop. The second and the third stages are most affected by the variables in Table 1. In particular, hard work, greater depth, and colder temperature may cause early canister "breakthrough" in which a physiologically significant level of CO_2 appears in the inspired gas.

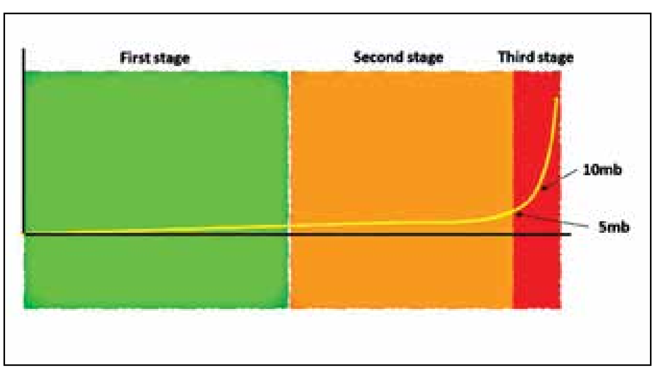


Figure 1. CO_2 curve for inspired gas.

CO_2 sensors for inspired gas: detecting breakthrough or seal failure

A CO_2 sensor in the inspired gas would allow detection of a mechanical seal failure or CO_2 breakthrough. Non-dispersive infrared CO_2 sensors have been available for some time and operate on the principle that light passing through various gases is absorbed at different frequencies. Early infrared sensors used a light source, filter, and detector, but recent sensors replaced the filter with a "tuned" light source with improved sensitivity and reliability. Several stable sensors are available, but they must not be exposed to more than 95 percent humidity. For use in the 100 percent humidity environment of a rebreather, additional filtration and software are required. Compensation for changes in depth and gas mix are also an issue. VR Technology has the only commercially available infrared sensor for rebreathers, although sensors are under development by other manufacturers.

CO_2 sensors for expired gas: detecting physiological CO_2 retention by "breath-to-breath" analysis

While measurement of CO_2 in the inspired gas is important to detect rebreather malfunction or canister exhaustion, the body can retain CO_2 if respiration is too low for adequate elimination. This can occur due to respiratory or equipment deadspace, increased work of breathing (WOB) due to heavy exercise, increased gas density, resistance to gas flow in the breathing loop, or respiratory muscle fatigue. If the diver cannot eliminate all the CO_2 that is produced because ventilation is inadequate, CO_2 retention, hypercapnia, and CO_2 toxicity are likely.

To detect physiological CO_2 retention, the partial pressure of CO_2 (PCO_2) must be monitored throughout the entire breath, and this requires a sensor that that has a wider dynamic range and faster response time than a sensor suitable for inspired gas. CO_2 retention is indicated if PCO_2 at the end of expiration (end-tidal) exceeds normal limits. Under most conditions, the problem is correctable by relaxing and stopping work, but it is a clue to the diver that the dive is not going well, and corrective action, if not aborting the dive, is necessary. CO_2 sensors that are capable of breath-by-breath measurement are also good for inspired CO_2 but will probably not be available for operational use for at least two to three years. When they are available for rebreathers, however, the CO_2 safety problem will be greatly improved.

Predicting remaining CO_2 canister duration

The oldest prediction method is a simple timer based on the "worst case" or shortest canister duration measured during chamber tests at a high simulated workload (1.6 L of CO_2 per minute), low temperature (39°F [4°C]), and either 130 or 330 ft (40 or 100 m). If the rebreather has a computer, the timer will warn the diver with an alarm as the limit approaches. These limits are likely to be overly conservative as most dives are conducted in warmer water and lower workloads.

A more sophisticated method is the "metabolic rate" timer that monitors oxygen addition to simulate oxygen that is being metabolized by the diver to estimate the CO_2 volume that is produced. Neither the simple timer nor the metabolic rate option can detect seal failure or breakthrough.

A third approach is a "thermal array" that detects the thermal wave front and indicates the location of the currently active section of the absorbent bed as it moves through the canister. This method allows an estimate of how much absorbent has been used and how much may remain. There are several variants made by Ambient Pressure Diving, rEvo, VR Technology, and the U.S. Navy. This method gives the most accurate prediction of remaining time with a fresh canister and no changes in depth, temperature, or workload. Should changes occur, however, prediction errors are introduced because the system is slow to react. This is a particular problem if the canister was used on a previous dive and is not fresh or the absorbent becomes wet. In these cases, the start-up time needed for the chemical reactions to stabilize introduce inaccuracies.

What divers know about their canister limits

The number and types of rebreathers has increased substantially over the last 10 years. To gain an appreciation of how well rebreather divers understand the limitations of their CO_2 absorbent systems, we conducted an Internet survey over a three-month period. Figure 2 summarizes the 323 responses over 25 rebreather types, eight of which were "home built." Not all surveys were complete. The following figures summarize the results.

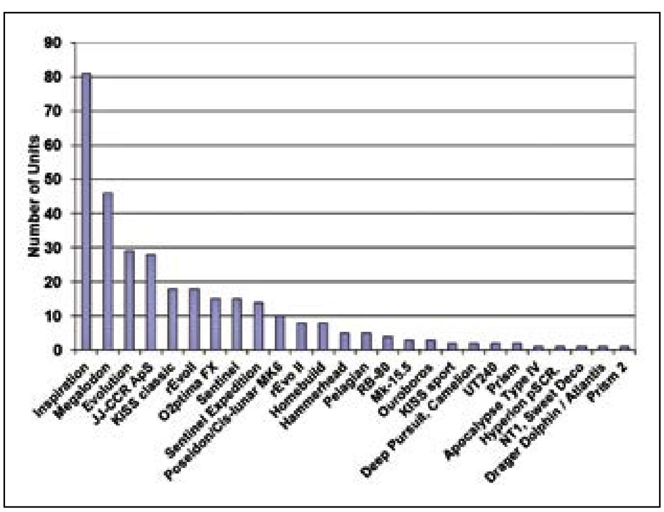


Figure 2. Types of rebreather from 323 survey responses.

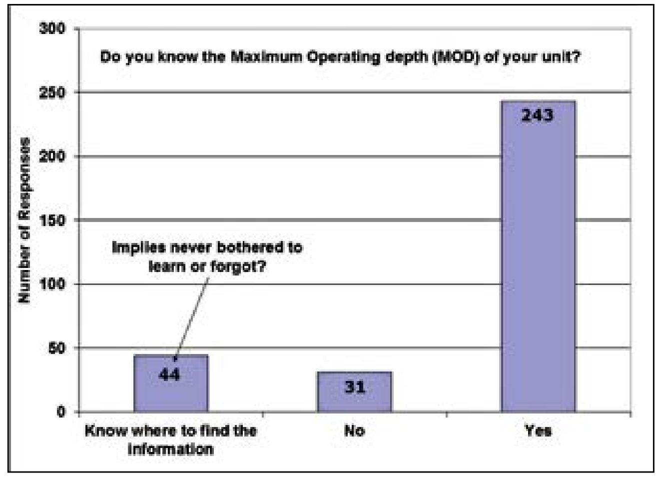


Figure 3. Knowledge of maximum operating depth (MOD).

Figure 3 summarizes the responses of 318 people to the question, "Do you know the maximum operating depth (MOD) of your unit?" Of the respondents, 76.4 percent said yes, 9.7 percent said no, and 13.8 percent said they knew where to find it. Thus, 23.5 percent did not know their MOD. Multiple MODs were reported for the same unit, in some cases up to four answers.

CO_2 scrubber duration is influenced by depth, absorbent mass, absorbent type, water temperature, rebreather design, ventilation rate and CO_2 production. Figures 4-6 summarize the responses of 323 people who responded to the question, "Do you know your CO_2 canister duration, its operating temperature/depth, and the duration at this temperature/depth?"

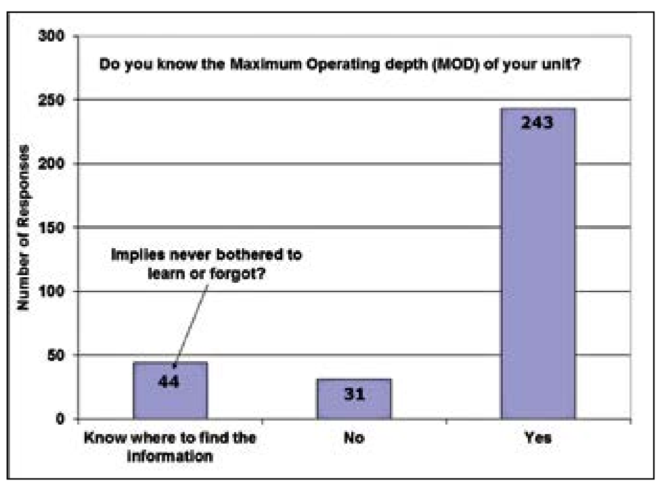


Figure 4. Knowledge of canister duration.

Figure 4 indicates that 18 percent appeared not to know the duration of their absorbent. Figure 5 indicates that 26 operating depths for CO_2 duration were reported. Most manufacturers specified two operating depths, nominally, 130 and 330 ft (40 and 100 m). Figure 6 indicates that while most manufacturers specify canister-duration limits for two temperatures, survey respondents reported 22 operating temperatures.

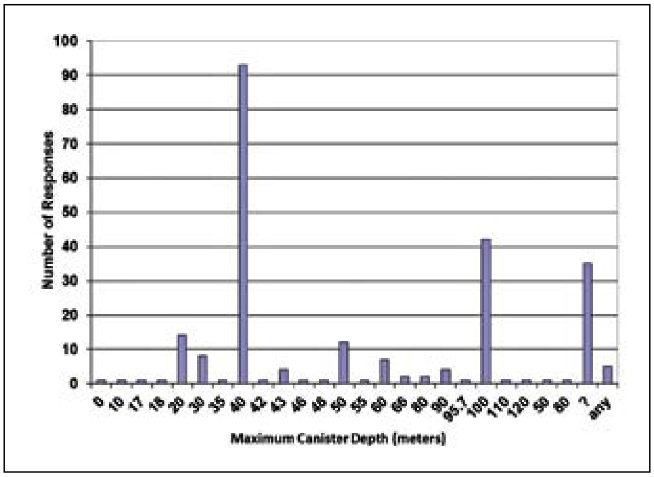


Figure 5. Knowledge of operating depths.

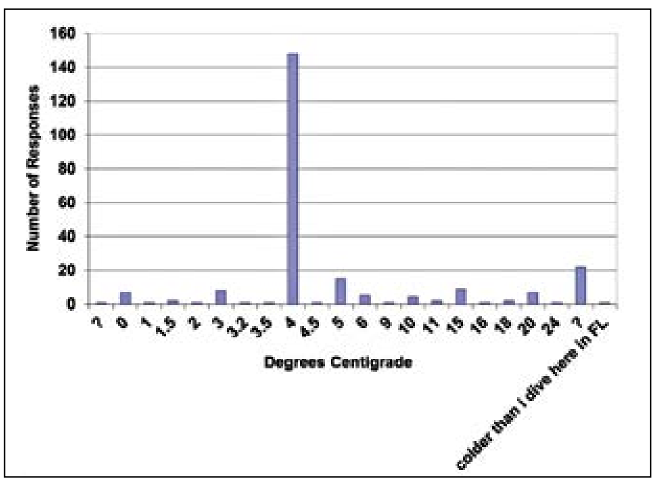


Figure 6. Knowledge of operating temperatures.

Figures 7-9 summarize the responses to, “Have you ever exceeded your canister alarm, did you bailout, what symptoms did you have?” Figure 7 summarizes 297 reports of symptoms that were consistent with hypercapnia. Some people reported more than one symptom. In Figure 8, 41.5 percent reported they had exceeded their canister alarms but indicated that if they had hypercapnia, they could “deal with it.” Of those who had symptoms, 16 percent bailed out and 64 percent did not bailout (Figure 9).

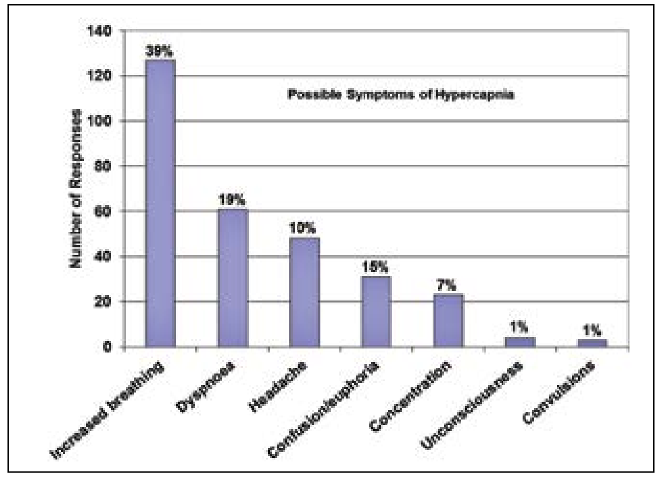


Figure 7. Reported symptoms of possible hypercapnia.

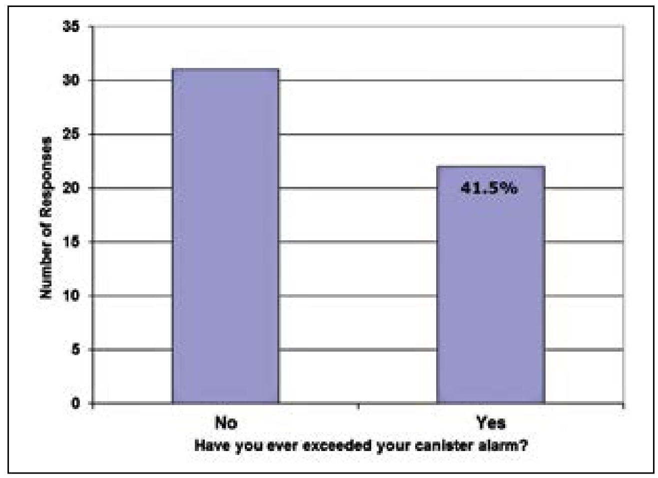


Figure 8. Reported exceeding canister alarm.

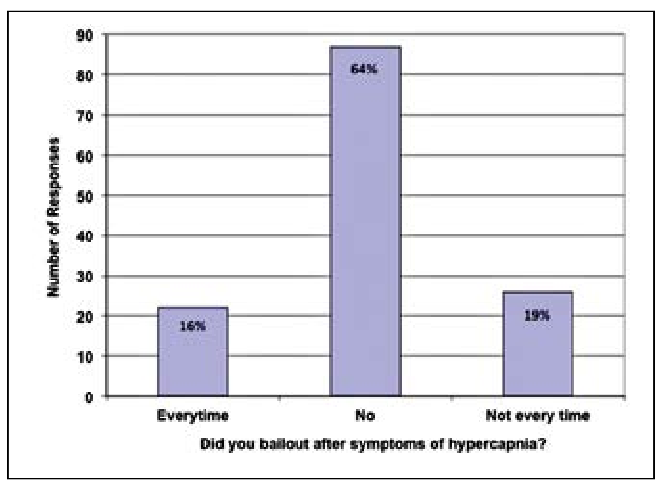


Figure 9. Reported bailouts after symptoms of possible hypercapnia.

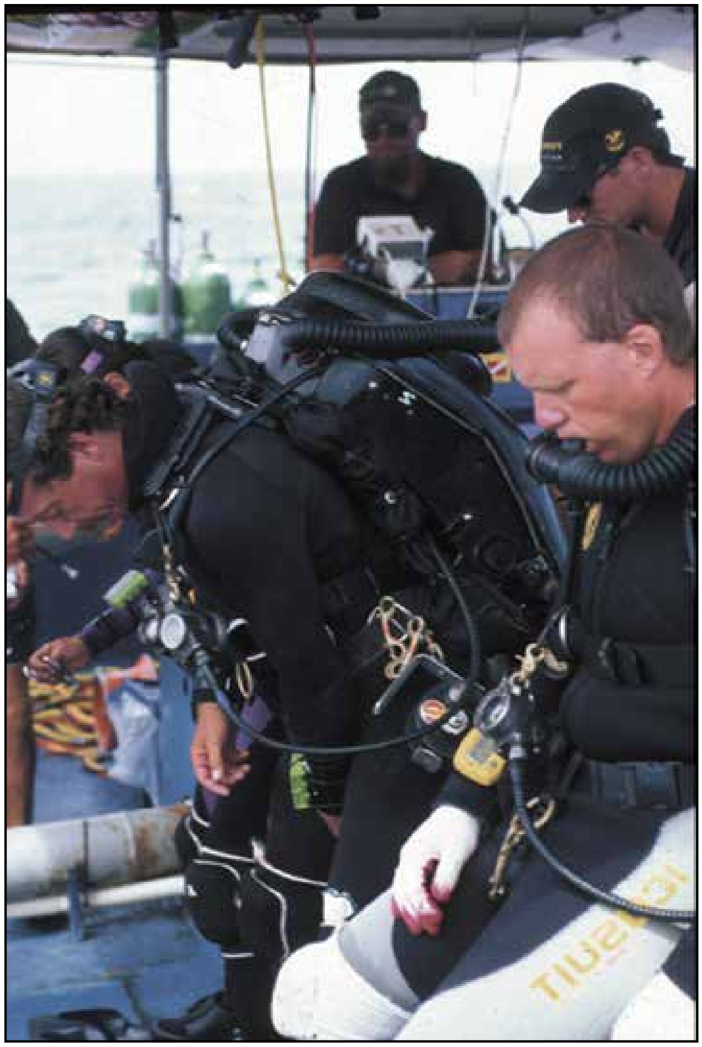
Because of the wide range of answers to the questions above, we did an Internet search for two popular rebreather manufacturers to see if information on canister duration was readily available. We easily found summary information on their websites, which also pointed to the operations manuals. It would appear that few divers visit the websites or read the manuals and that emphasis on canister duration during training is inadequate or easily forgotten. Manufacturers might publish more detailed canister information on their web pages and perhaps affix a label with this information on the canister itself.

SUMMARY

Equipment, physiological, and environmental factors influence the duration and safety of CO_2-management systems in rebreathers. Sensors that measure inspired CO_2 are beginning to appear and represent a major improvement in safety by detecting canister breakthrough or mechanical failure. Sensors for measuring end-tidal or breath-to-breath CO_2 are some years away from practical implementation but will allow detection of physiological CO_2 retention by the diver. Predicting the remaining duration of a CO_2 canister is an inexact science, although useful methods exist, including using a simple timer, a metabolic rate timer, and the thermal array. Perhaps more disturbing is that divers do not appear to have accurate knowledge of even the simplest limits of the CO_2 canisters to which they entrust their safety.

Truk Lagoon. Photo by Kevin Gurr.

Betty Bomber. Sentinel Rebreather. Photo by Drew Trent.



MK15.5 diving. Photo by Kevin Gurr

Arctic diving. Photo by Leigh Bishop.

CO_2 SCRUBBER TECHNOLOGY: WHY, HOW AND HOW LONG

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ABSTRACT

People exhale CO_2 during normal activities. The CO_2 has to be removed from the breathing circuit of a rebreather. Several techniques exist, the most common is chemical absorbent. The absorbent gives the rebreather a limited endurance time. The endurance time depends on several factors, such as water temperature, depth, diver workload, CO_2 scrubber size and the material used. The actual endurance time is very hard to predict — worst-case times are typically given. Inspired CO_2 should make divers breathe more, but not all divers do. Such CO_2-retaining divers run the risk of (severe) headaches, tunnel vision, confusion, increased decompression problems and O_2 toxicity. Few divers are able to detect CO_2. Real-time monitoring of the scrubber would reveal remaining capacity during a dive. Measuring the CO_2 in the inspired gas will reveal channeling in a scrubber. However, a normally functioning scrubber will remove all CO_2 for most of the dive, and a CO_2 sensor will not allow any planning. Measurements inside the scrubber show characteristic changes in the temperature. Such changes allow predictions of remaining capacity that would allow a diver to use available absorbent, thus safely extending a dive and reduce the cost of rebreather diving.

Keywords: absorbent, carbon dioxide, control of breathing, diving, endurance, hypercapnia removal, scrubber

INTRODUCTION

A diver who uses a rebreather (closed-circuit and semiclosed-circuit apparatus) relies on the rebreather's ability to remove the exhaled CO_2. In this paper I will highlight the following:

- why CO_2 removal is essential and consequences of inspired CO_2,
- ways to remove the CO_2,
- ways to determine how long the CO_2 scrubber actually lasts,
- factors that determine scrubber efficiency,
- how to monitor a scrubber during a dive.

SOURCE OF CO_2

Rebreather divers should know that the human body consumes O_2 in proportion to how hard they work. Related to this O_2 consumption is the body's production of CO_2 — it is a byproduct of normal living. The volume of CO_2 produced is normally somewhat less than the volume of O_2 consumed. However, if a diver works hard enough to generate lactic acid in the muscles, then the volume of CO_2 exhaled will exceed the volume of O_2 consumed.

WAYS TO REMOVE CO_2

The commonly used way for rebreathers to remove the CO_2 is by chemical absorption. Several types of materials can be used, often various hydroxides (e.g., lithium hydroxide, sodium hydroxide, calcium hydroxide) in various combinations. These materials have different efficiencies when it comes to CO_2 absorption, and their abilities change with temperatures. Lithium hydroxide is probably the best at low temperatures, but it may be corrosive both to the rebreather and the diver. Even dust particles small enough that they are hard to see can cause the diver to cough from irritation.

There is a group of materials called superoxides that release O_2 when they absorb CO_2. This sounds like a nice feature for a diver using a 100 percent O_2 rebreather. However, if the superoxide produces more O_2 than it absorbs CO_2, the partial pressure of O_2 (PO_2) cannot be reduced. This would become a problem after a descent when the PO_2 tends to overshoot. A big disadvantage with superoxides is that they tend to react violently with water.

It may be possible to use cryogenic O_2 to freeze out CO_2 (freezing points are -183°C [-297°F] and -56°C [-69°F], respectively). However, water vapor condensation/freezing will have to be considered.

In some industrial settings and in some military submarines, materials called amines are used to regenerate the atmosphere. This liquid absorbs CO_2 when cool and releases it again when heated. Because of the need to heat and cool the amine, it requires a fair amount of power and has put it outside the reach of rebreather diving.

HOW TO DETERMINE HOW LONG A SCRUBBER LASTS

Most rebreathers have no way of telling the diver much longer it can remove the CO_2. Therefore, the scrubber endurance has to be determined in other ways. To get repeatable results that can be compared with results from different test houses breathing simulators are used instead of divers. For these tests a breathing simulator has to breathe and produce CO_2 like a diver. It also has to exhale warm and humidified gas the way a diver does (see Figure 1). On the right is a piston that moves inside a cylinder. The movement generates the correct volume for a breath, and the frequency of it determines the breathing

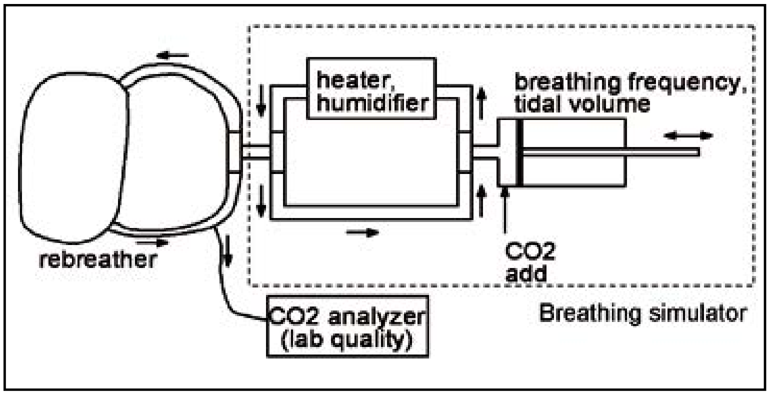

Figure 1. Schematic of the test set-up for determining the endurance of a CO_2 scrubber. The rebreather to be tested is on the left. The interrupted line encloses the parts of the breathing simulator. Arrows indicate the piston movement and gas movement, respectively.

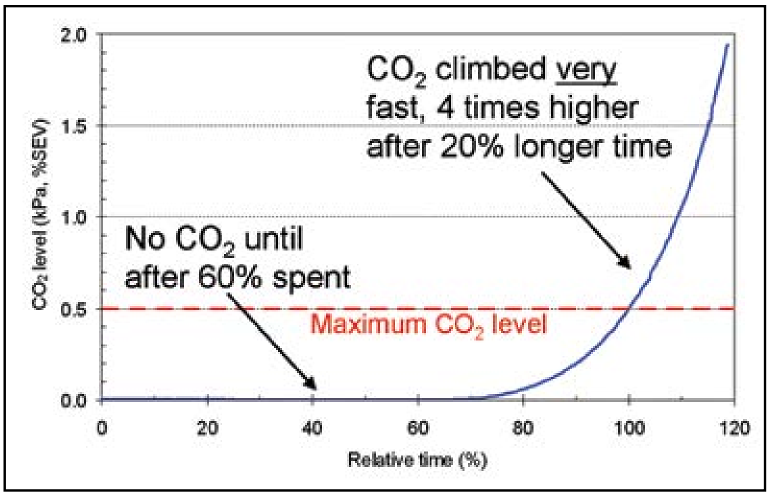

Figure 2. Common variations in the CO_2 levels measured in the inspiratory hose during a dive. The red, interrupted horizontal line indicates the maximum acceptable CO_2 level.

frequency. CO_2 is added into the cylinder, where it mixes with inhaled gas. Before the gas reaches the rebreather, it passes through a heater and humidifier. The rebreather's mouthpiece is attached to the breathing simulator's gas opening. To monitor the scrubber, the CO_2 level in the inspiratory hose is monitored with a laboratory-quality CO_2 analyzer. Some breathing simulators can also consume O_2 and are used to determine a rebreather's ability to control the PO_2.

Endurance tests of a scrubber are run at the desired temperatures and depths. The rebreather must be immersed and inside a hyperbaric chamber. The breathing simulator is set to simulate the desired workload, anything from rest (e.g., decompression) to very hard work (e.g., swimming upstream to get back to the boat). This means breathing 10 or 20 $L{\cdot}min^{-1}$ all the way up to 100 $L{\cdot}min^{-1}$. Some simulators can breathe up to 150 $L{\cdot}min^{-1}$. The latter minute ventilation is one that only top athletes can sustain, thus it is far more than a diver typical needs. The CO_2 is added in proportion to the minute ventilation — i.e., in the range 0.4 to 4 $L{\cdot}min^{-1}$. This type of testing is far beyond what divers can do themselves.

It turns out that the amount of CO_2 that a scrubber can absorb varies with many factors — i.e., the volume of CO_2 absorbed is far from constant. Ideally, endurance tests should be run at several water temperatures, depths and workloads to get the full range of scrubber performance. If tests were run at each of three temperatures, three depths and three workloads, we would need 27 tests. If five rebreathers were tested in each condition to get statistical certainty, we would need 135 tests. Depending on the scrubber endurance, only one or two tests can be run per day. That means somewhere between 14 and 27 weeks of testing. Ideally, these tests should be run for more than one absorbent, for dives where depth and temperature vary and for dives where the canister was partially used. Obviously, this is an essentially impossible task.

To reduce the time for these tests, they are typically only run as worst-case scenarios: A fairly high workload is used in cold water at the maximum depth. In practice: the minute ventilation is 40 $L{\cdot}min^{-1}$, CO_2 is added at 1.6 $L{\cdot}min^{-1}$ and the water temperature is 4°C (39°F). The outcome is meant to give a safe estimate of the actual endurance. As with any worst-case estimate, it is pessimistic.

The CO_2 level in the gas leaving the rebreather does not increase linearly with dive duration. Figure 2

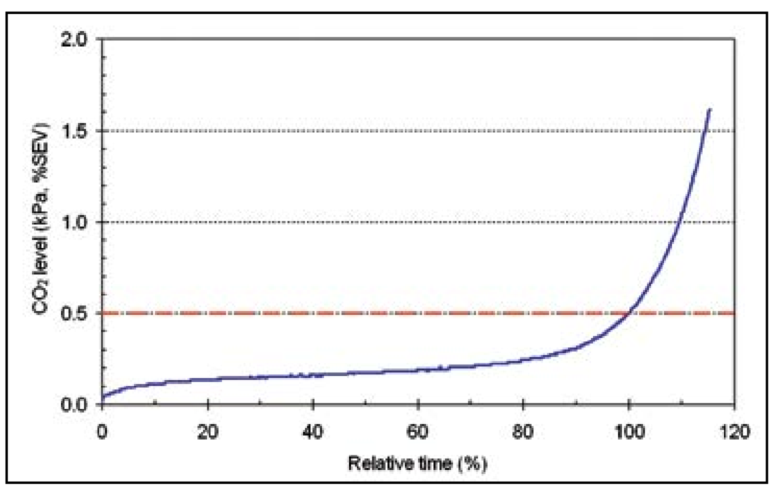

Figure 3. Other variations in the CO_2 levels measured in the inspiratory hose during a dive.

shows a typical pattern of how the CO_2 in the inspiratory hose changes during a dive. Note that, in this example, all CO_2 is removed up to 65-70 percent of the endurance. At that point the CO_2 starts to climb very quickly. In fact, after the CO_2 has passed through the breakpoint, it increased to be four times higher after only 20 percent more time.

In Figure 3 we see a different, less-common pattern to the changes in CO_2. The CO_2 climbs from the very beginning and reaches a low and almost stable level until about 80-90 percent of the endurance. After that, it climbs as fast as the trace in Figure 2.

FACTORS THAT INFLUENCE SCRUBBER EFFICIENCY

Several factors determine how efficient a scrubber can be. The geometry of the scrubber itself and the scrubbing material are two factors. The water temperature, diver workload and depth are other factors.

Scrubber geometry. Most scrubbers can be seen as having either axial flow or radial flow. The upper scrubber in Figure

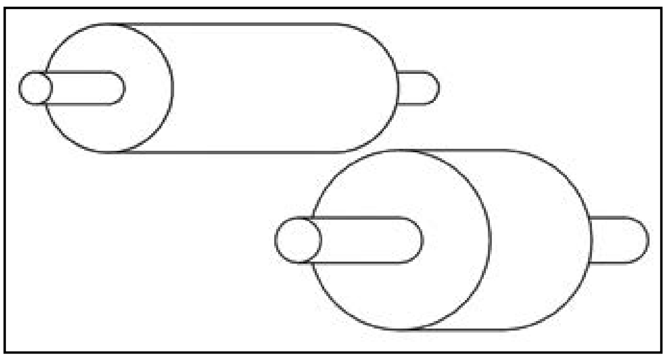

Figure 4. Illustration of two types of axial scrubbers.

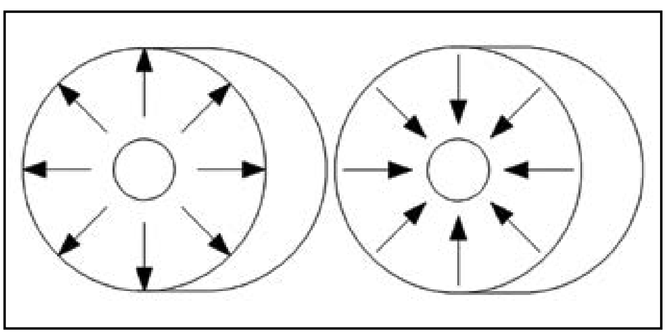

Figure 5. Illustration of two types of radial scrubbers.

4 is long and narrow with an axial flow (gas enters on the left, flows along the scrubber axis and exits on the right). The lower scrubber is short and wide. The scrubber cross section is often circular or oval. Figure 5 shows a radial scrubber. In the left scrubber, gas enters in the middle and travels along the radius (of the circular cross section) to the outside. In the scrubber on the right, the gas travels the other way.

Absorbent size. Granular absorbent comes in several sizes, quantified by a number. The smaller the number, the larger the grains. A fine-grain absorbent has more surface area and tends to absorb CO_2 more efficiently. The drawback is that its breathing resistance is higher. Conversely, a course-grain absorbent has less breathing resistance but tends to be less efficient. A balance between the ability to breathe and endurance must be found. Solid absorbents (i.e., absorbent mixed with a binding material and extruded) has similar tradeoffs between surface area and breathing resistance. The manufacturer must decide on the dimension of the ridges.

Absorber packing. The endurance will vary even when the same person packs a canister with absorbent from the same container. Normal variation in endurance time is 5-10 percent.

You breathe what you ate. Even for a fixed work rate (O_2 consumption) the amount of CO_2 exhaled will vary. The amount depends on what the body is using for fuel (fat, protein, carbohydrates) for the working muscles. The CO_2 production may vary by ±15 percent. Work that is hard enough to generate lactic acid in the muscles may increase the amount of exhaled CO_2 by 20 percent.

Other factors. The size of a scrubber affects the efficiency, too. A large scrubber tends to be more efficient; think of it as the time that the exhaled gas remains inside the scrubber (dwell time). If the dwell time is large, then the absorbent has a better chance of picking up the CO_2. Dwell time is also affected by the diver's minute ventilation: The more the diver breathes, the shorter the dwell time, which means less efficiency.

Examples. Assume that you have a rebreather whose scrubber is rated for two hours at a temperature of 15°C (59°F). If this rebreather is used the same way in cold water, say 4°C (39°F), the endurance may decrease by 35 percent (based on actual measurements). The two-hour duration will then be only 80 minutes. An increase in water temperature from 15°C to 30°C (59°F to 86°F) may increase the endurance by 25-40 percent. The two hours will then be 2.5-2.75 hours.

If the diver has to work harder (e.g., swimming against the current to get back to the boat) than the workload when the two-hours endurance was determined, the endurance may drop by 50 percent. The two-hour scrubber will then last only one hour. If the workload is light instead (e.g., decompression), then the scrubber endurance may double, i.e., it may last four hours.

If the diver is working hard in cold water, the scrubber may be used up in 30 minutes. Light work in warm water may allow a six-hour endurance.

The diving depth will also affect endurance. The deeper a diver goes, the shorter the endurance. The actual changes will depend on the absorbent used.

The combined effects of temperature, workload and depth can influence the endurance to be anywhere from 30 minutes to 6 hours. Actual measurements of the endurance have shown that it can vary by a factor of 5-20. The actual endurance time is far from a fixed number.

If you give the scrubber a chance, it will remove more CO_2. Put differently, if you stress the scrubber, it will remove much less CO_2. This wide range of actual endurances is probably why some divers can dive their rebreather well beyond the stated endurance. Such divers are certainly taking risks by following this practice. In other words, if you rely on this type of diving, you may not come back one day.

Efficiency is a parameter that describes how much CO_2 a practical scrubber will absorb in relation to the amount it can possibly absorb. A 100 percent efficient scrubber would be one that uses every last amount of the absorbent available, but it would take an infinite length of time. Most of us do not want to wait that long before we breathe again, so we will not see a practical scrubber that is 100 percent efficient. The upper range of usable scrubbers may be some 80 percent, the low range may be as low as 5 percent.

INFLUENCE OF INSPIRED CO_2

There are three ways for a person to react when the inspired gas contains extra CO_2:

- breathe more, and keep the CO_2 level in the body the same;
- breathe the same amount of gas, and allow the CO_2 in the body to climb; or
- a mixture of these.

This CO_2 can come from the mouthpiece or a full-face mask. Consider a snorkel: As a person exhales, the snorkel fills with CO_2-rich gas. At the beginning of the following inhalation, the person gets the unwanted gas back. To get the same amount of fresh gas, the person should breathe more.

The body controls the CO_2 quite well, but it is not perfect. The textbook value for this CO_2 level is 40 mmHg (5.3 kPa, 5.3 percent SEV). Typically, it increases slightly during exercise and decreases at rest. Many working divers will let their CO_2 climb to 6 kPa. If such a diver inhales a gas containing 0.5 kPa (5 mbar, 0.5 percent SEV), the minute ventilation will have to increase by 9 percent to maintain the 6 kPa. If the gas contains 1 kPa CO_2, then the increase will be 20 percent; if the gas contains 2.0 kPa, the increase will be 50 percent. The need to breathe increases drastically with inspired CO_2.

Increases in inspired CO_2 are a real reason for concern. Despite what people think, few divers can recognize increased levels of CO_2. We have run experiments where experienced divers are breathing gas with elevated CO_2. Some increase their minute ventilation, but some do not. Their CO_2 levels have increased to such levels that we had to stop them for safety reasons. They were not aware of their dangerous situation.

Normally the body's control system takes care of breathing, similarly to how your heart rate changes in response to increased work. However, CO_2 is a gas with narcotic properties — high levels will impair judgment and may even cause loss of consciousness. Other effects are (severe) headaches, tunnel vision, irritability, inability to remember instrument settings and panic symptoms. The CO_2 narcosis is additive to any nitrogen narcosis. High CO_2 levels increase the risk of O_2 convulsions and the risk of decompression sickness.

Some divers are CO_2 retainers: They do not breathe enough and maintain high levels of CO_2 (hypercapnia). A concept used by scuba divers is to save air, the consequence is increased CO_2 levels. Such CO_2 retainers are at greater risk than others. A rebreather diver has no need to try to save air.

The breathing resistance in the rebreather makes the body's control of breathing worse. The breathing resistance makes it harder to increase the minute ventilation needed to compensate for the inhaled CO_2.

Switching to open-circuit gas will remove most inspired CO_2, but it takes at least several minutes before the effect has worn off. Headaches may take hours to go away.

HOW TO DECIDE ON ACTUAL ENDURANCE

Several parameters have to be considered when the endurance time is determined: the level of acceptable inspired CO_2, variation from tests to test and what happens to the CO_2 after the limit has been reached.

The limit on inhaled CO_2 has to be fairly low for two reasons: 1) the severe consequences of high inhaled levels of CO_2; and 2) the very rapid change in the CO_2 level of the gas leaving the scrubber at the end of the dive (Figure 2). The limit chosen for the inspired CO_2 is 0.5 kPa (5 mbar, 0.5 percent SEV). The actual inhaled CO_2 will be higher due to the deadspace of a mouthpiece or full-face mask. It would be dangerous to raise this limit, possibly very dangerous.

When testing the endurance of a scrubber there is always some variation from test to test, even under identical conditions. The same will happen during normal diving. To determine the amount of variability, several tests (say five) must be run. The average endurance time and the variation can be calculated. Statistical analysis will be used to calculate an endurance time such that it gives a 95 percent (or more) certainty that the CO_2 will not exceed the limit. The endurance time will be shorter than the average of the test results.

MONITORING THE SCRUBBER DURING A DIVE.

Today's rebreather divers' way of using their scrubbers is very much like driving a car where:

- you empty the fuel tank, and fill it again before diving;
- from the time you start the car you have only certain time of use — no matter how you drive.

This is not really a good way, but it is the only way we have been able to do it.

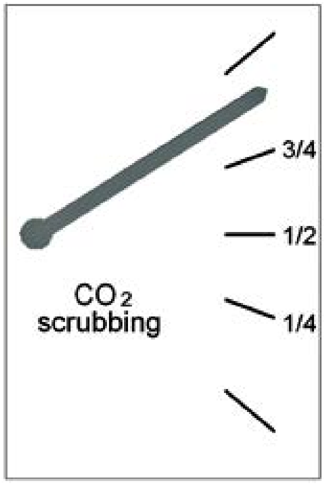

Figure 6. Illustration of an ideal scrubber gauge.

It would be nice to have a gauge that tells you how much is left of the scrubber — something like a pressure gauge and that tells you how much breathing gas you have left. After all, would you dive without a pressure gauge? Would you drive a car without a fuel gauge?

Figure 6 shows how an ideal scrubber gauge could look. It looks very similar to a fuel gauge and a pressure gauge because people are used to these and would not need much training in interpreting them. An ideal scrubber gauge would have several design goals:

- It must be accurate.
- It must not be sensitive to temperature, depth, humidity, condensation or previous absorbent use.
- It should not require any maintenance.
- It should use minimal power.
- It should not need calibration or at least only infrequent calibration.
- It must tolerate salt water.
- It must tolerate the caustic environment.

The obvious solution may seem to be a CO_2 sensor. However, the environment of a rebreather is one of the hardest to work in, and a CO_2 sensor would be challenged. The temperature varies (the scrubber can reach 55°C (130°F). The gas is 100 percent humidified; water (that the scrubber makes) will condense. Some CO_2 sensors' techniques (such as infrared sensors) are sensitive to gas composition and pressure. A battery should last at least a dive. The diver needs to know that the sensor actually works (i.e., calibration). What is the cost? These challenges are not impossible, and some day somebody will find such a CO_2 sensor.

However, the biggest drawback of a CO_2 sensor is that there is usually no CO_2 to sense. Figure 2 showed the typical variation in CO_2 during a dive: no CO_2 until 60-80 percent of the scrubber is spent. A CO_2 sensor would read zero most of the time. This is, of course, what a diver wants, but when it starts to read something other than zero, the diver may be more than halfway through the dive and should have turned around already. A CO_2 sensor does not allow any planning — it can be a warning only. It would be like driving a car using only the warning light that comes on you are very low on fuel. However, a CO_2 sensor would tell you about channeling in a badly packed scrubber.

Another way to monitor the scrubber. It is well known that the absorbent gets warm when a diver breathes through it — the chemical reaction is exothermic. Would temperature sensors in the absorbent (Figure 7) be able to tell the story?

Think of the scrubber as a loaf of sliced bread with a temperature sensor in each slice. Figure 8 shows a recording illustrating how the temperatures changed in several location in the absorbent through a test. At the start of the test the temperature at

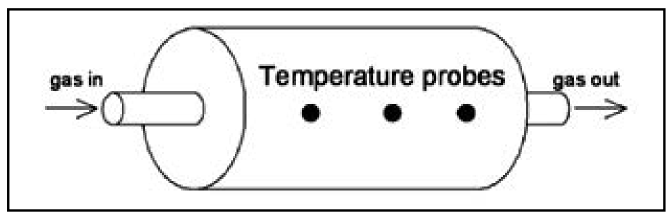

Figure 7. Illustration of temperature sensors in a CO_2 scrubber.

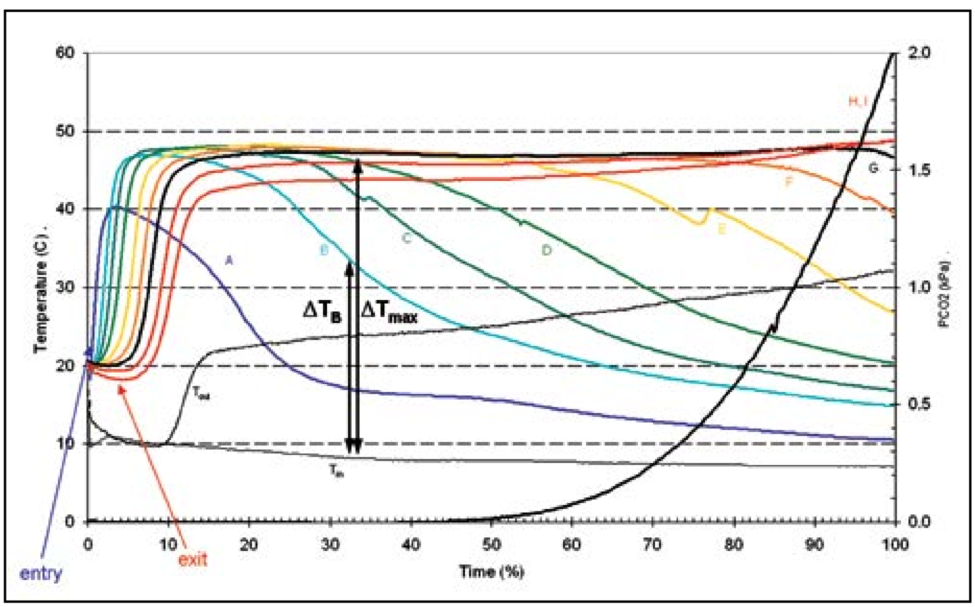

Figure 8. Temperature variations recorded from nine sensors placed in a CO_2 scrubber and the CO_2 in the inspiratory hose. Temperatures are shown on the left vertical axis and CO_2 level on the right vertical axis. Time is expressed as a percentage of the entire run; 100 percent does not mean the time to a physiologically acceptable CO_2 level.

the scrubber entry (probe A) starts to rise first as the warm, humidified and CO_2-rich gas reached the absorbent. The temperature of the other slices then rises in sequence. Quite soon the temperature of the first slice (probe A) peaks and starts to fall, indicating that it is mostly spent. Sometime later probe B peaks and starts to fall, a pattern followed by the remaining sensors but at different times. It looks like a warm front is traveling through the absorbent first, followed by a cold front.

The actual temperatures seen vary with water temperature (lower in cold water) and depth (lower as depth increases), but the pattern remains. So how can this nice and colorful picture be turned into something useful? There are at least two ways of doing so. One way is the one used in the Inspiration rebreather, which has a "temp stick" that shows the "scrubber health." The method is described in a UK patent (Parker, 2005) and an EU patent. Another method is the one used in the Sentinel and the rEvo rebreathers that give a scrubber gauge readout. The method is described in U.S. (Warkander, 2003) and other patents. The latter method will be described in some detail here.

The first step in generating a scrubber gauge is to calculate how much the temperature of the absorbent has increased. Figure 8 shows the temperature of the gas about to enter the absorbent as T_{in}, starts around 10°C (50°F) and decreases to about 8°C (46°F). At time about 33 percent, probe B (ΔT_B) indicates that the temperature has increased by about 23°C (73°F). The temperature increase is less at depth because of the gas density (larger thermal mass), so the change in temperature itself is not necessarily enough. The second step is to determine the largest temperature increase at the same moment, the largest increase (ΔT_{max}) at time 33 percent is about 38°C (100°F). By calculating the ratio of these two increases it is possible to get values that are essentially independent of water temperature and depth. In this case the ratio would be 23/38 = 0.61. As the test continues, ΔT_B decreases and the ratio decreases, too. ΔT_B shows substantial changes between times 25 percent and 50 percent. Readings from other probes can be used to cover the entire dive, and the ratio can be calculated for the probes chosen (not all nine are needed). When the ratio has dropped to a certain value the gauge should read empty (zero). The exact value depends on the location of the probes that are used.

Figure 9 illustrates what a scrubber gauge may read based on a different rebreather at a different depth than that shown in Figure 8. Simple curve fitting can straighten the curve.

During a normal dive the workload of a diver is unlikely to be the same throughout a dive. Figure 10 shows what happened to the scrubber gauge reading and the CO_2 level when the workload alternated between low and moderate. The CO_2 trace shows that the scrubber was more able to remove the CO_2 during the low workload, the low part of the sawtoothlike pattern. Interestingly, the scrubber gauge reading has a similar sawtooth pattern that started from the very beginning of the dive. It looks very odd in that the reading increases when the workload decreases. After all, your car's fuel gauge does not increase when you drive down a hill. Well, maybe if you have a hybrid car. However, the gauge should do exactly that since the scrubber is more efficient at low workloads and the remaining capacity is higher.

Something that is well illustrated in Figure 10 is the rapid and large change in the CO_2 level when the workload increases.

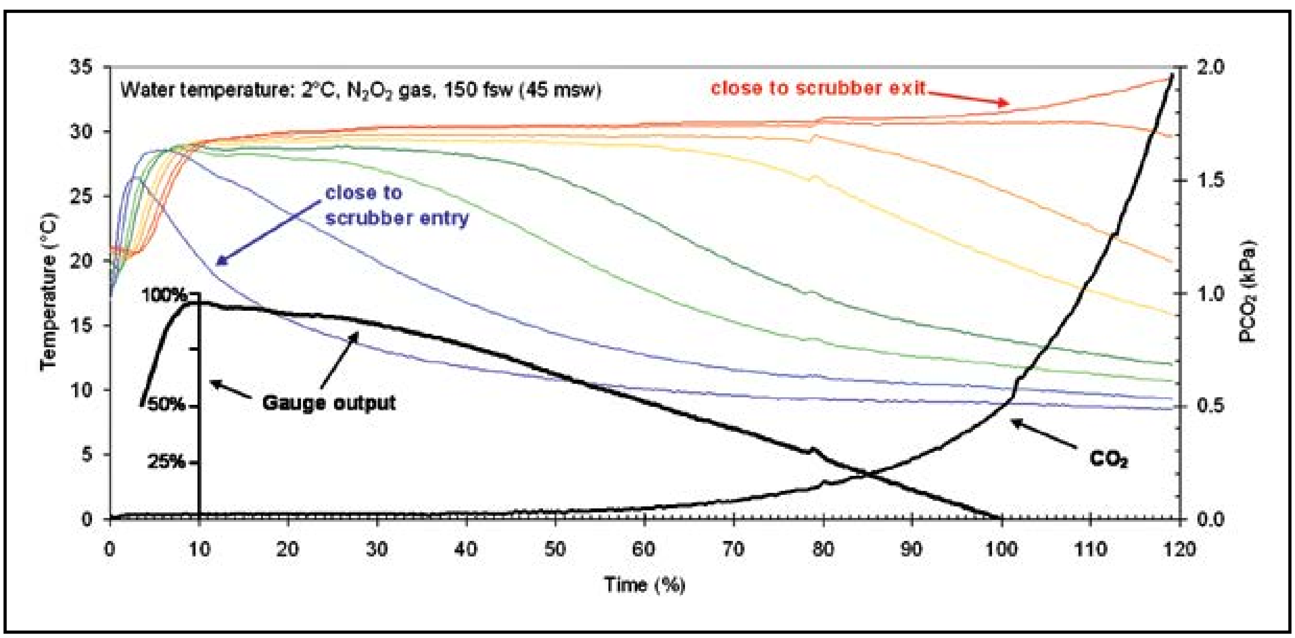

Figure 9. Temperature and CO_2 variations recorded from eight sensors placed in a CO_2 scrubber. The calculated gauge output is also shown.

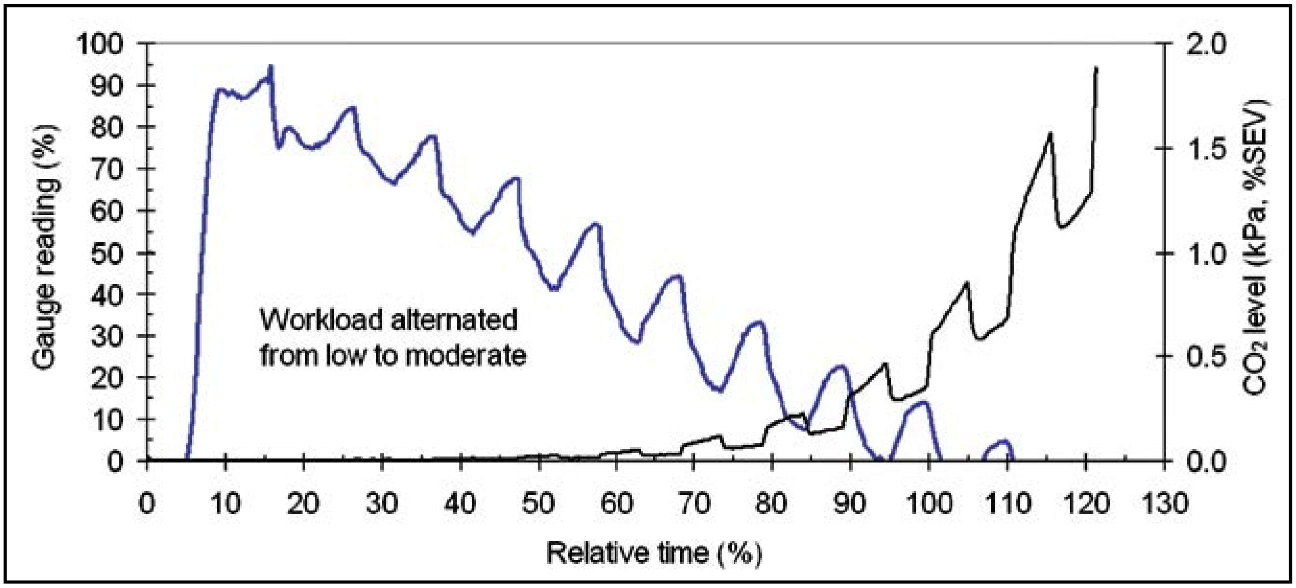

Figure 10. Variations in the scrubber gauge reading and CO_2 trace from a rebreather where the simulated diver workload varied.

At time point about 110 percent the CO_2 level rises rapidly from 0.6 kPa to 1.6 kPa (6 to 16 mbar) in a very short time and shows the dangerous situation that the diver is in. So for a diver who relies on using the scrubber far beyond its rated endurance, the CO_2 will climb quickly if hard work is needed at the end of the dive.

Figure 11 shows the proof-of-concept unit developed a few years ago for the U.S. Navy MK 25 (a version of the Dräger LAR V O_2 rebreather). Another unit has been built for the U.S. Navy MK 16 deep-diving rebreather that can be used with N_2O_2 and HeO_2 gases. To develop scrubber gauges for these two rebreathers and others, we obtained temperature recordings and did verifications for more than 4,000 hours. Tests with divers showed that the scrubber gauges work. A scrubber gauge is not something divers should develop by themselves.

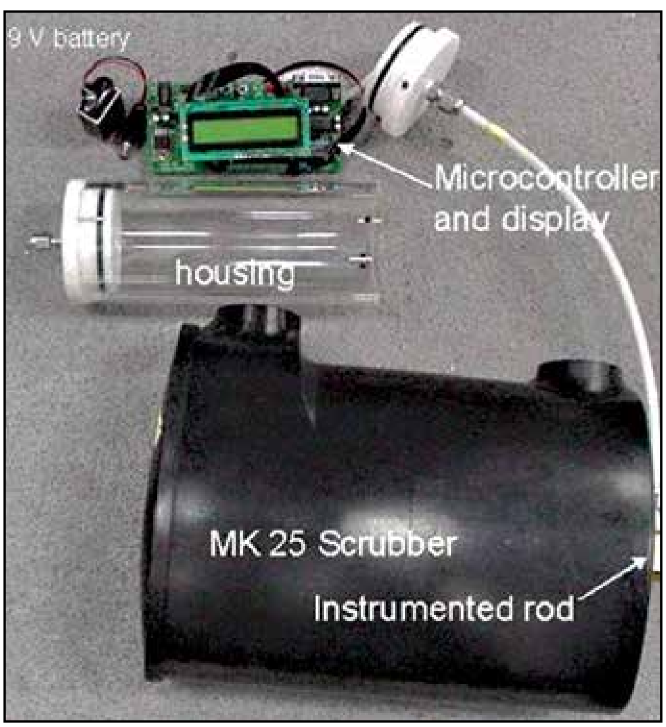

Figure 11. Photograph of the proof-of-concept unit developed for the U.S. Navy MK 25 100 percent O_2 rebreather. This unit was meant for verifications and demonstrations, not for field use.

Figure 12 shows the diver's display for three different stages of a dive. The top panel shows that the diver is not breathing on the rebreather or that there is no absorbent present. The middle and bottom panels show the progression of the dive.

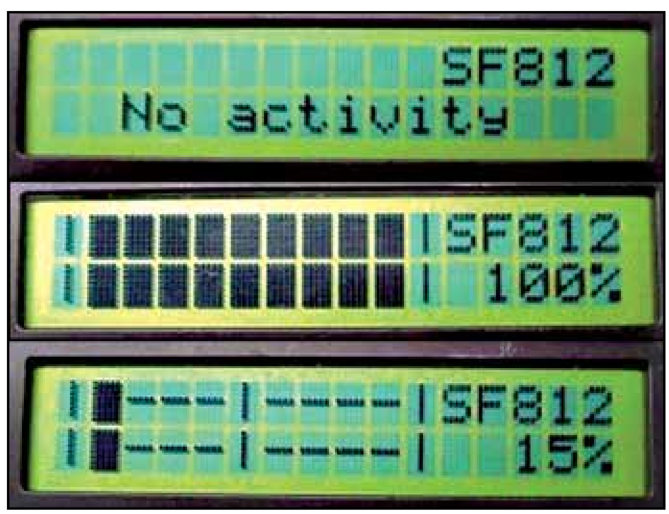

Figure 12. Photograph of the diver's display during different phases of a dive. The "SF812" refers to the absorbent used when the photo was taken.

SUMMARY

There are many techniques used to remove the CO_2 produced by the diver. The most common is the use of a chemical absorbent that has a limited capacity or endurance time. The endurance time is typically given as a single number, but the actual time can be much shorter or much longer.

The presence of CO_2 in the inspired gas is a real problem that is generally not understood or may even be ignored. The minute ventilation has to increase when CO_2 is inhaled. If not, the CO_2 in the body has to increase, which can cause (severe) headaches, tunnel vision and confusion, even panic. High levels may also affect decompression needs and increase the risk of O_2 toxicity. The CO_2 narcosis is additive to any nitrogen narcosis. The breathing resistance makes it worse. Few divers can sense elevated CO_2.

Early scuba diving was done without pressure gauges and buoyancy compensators. It was the practice then, but who wants to dive that way now? In a similar way, I think that every rebreather should have a real-time monitor of the scrubber. It would allow the diver to react to conditions during a dive. The diver would be confident that the scrubber works. The diver can safely use the absorbent available. The ability to monitor the scrubber would increase safety and reduce the cost of rebreather diving.

The opinions expressed here do not necessarily reflect the opinions of the U.S. Navy.

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Figure 13. USS Apogon, *Bikini Atoll, Marshall Islands. Photo by Andrew Fock.*

PREMARKET TESTING OF REBREATHERS: STANDARDS, CERTIFICATION AND TESTING

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ABSTRACT

Rebreathers are now used in many parts of the diving industry. To ensure that the risk associated with using rebreathers is as low as reasonably practicable (ALARP), performance standards, test procedures and certification have been established. The principle and status of the European Standard EN 14143 for rebreathers is presented. The requirements for premarket testing, performance standards, tests to be conducted and the current European certification processes are covered. Premarket testing is shown to be of benefit to the whole industry, including both manufacturers and end users.

Keywords: closed-circuit, diving

INTRODUCTION

The use of diving rebreathers has expanded far beyond traditional military application. They are now used extensively throughout the diving industry from saturation-diving bailout systems to media, scientific and recreational diving. To give all areas of the industry confidence that the safety of available systems is appropriate, methods of developing and assessing their performance are required. To achieve this, and before a system is placed on the market, it needs to go through a comprehensive development program of which testing and performance assessment are a vital part. The requirements for premarket testing and certification of rebreathers have been established but are continuously developing. This paper covers the principles of premarket testing, the advantages and limitations together with the current status of standards and certification that are being applied.

DIVING SAFETY CONSIDERATIONS

Diving, as with many other adventurous activities, has inherent risks; the deeper you go, the risk increases. It is unfortunately a reality that these risks can be exacerbated when the diver uses a rebreather. By design, rebreathers may be very simple or very complex. With the proliferation of electronically controlled rebreathers and the continuing parallel use of mechanical systems, both trying to closely control the breathing-gas mixture, we are seeing increasingly more complex systems.

A specific concern with rebreathers is that an incident associated with the increased risk is often linked to one of the three H's: hypoxia, hyperoxia and hypercapnia, all of which may have an insidious outcome. It is unfortunately apparent that there are too many incidents occurring with rebreathers and that many are fatalities.

To increase safety and reduce the risk of diving with rebreathers requires active contribution throughout the whole diving industry. However, an essential starting point is to ensure that the principle of operation and function of rebreathers is such as to minimize risk. One method of achieving this is by defining and demonstrating appropriate rebreather performance before they are used in water.

DEFINING REBREATHER PERFORMANCE

In defining rebreather performance, the overarching principle is that a rebreather needs to be "fit for purpose" to support the diving operations that each element of the industry requires. Divers go into a hazardous, extreme environment where they cannot breathe without equipment, have limited vision, may be clumsy and restricted in movement and need protection against cold. It is therefore clear that diving equipment, in this case a rebreather, needs to provide the diver with adequate and appropriate gas to breathe. This should be achieved while allowing the diver to easily move about, undertake any required tasks or to simply enjoy the underwater environment.

In providing protection from the environment the apparatus also has to protect the diver from its own inherent hazards. These can be mechanical failure, material failure or failure of the prime life-support function resulting in one or more of asphyxia, hypoxia, hyperoxia and hypercapnia. As an example, the first functional rebreather removed exhaled carbon dioxide from the breathing circuit by using a rope soaked in caustic soda; by removing a hazard from carbon-dioxide toxicity, an intrinsic hazard of caustic burns was introduced.

Thus in providing adequate protection and reducing risks the principle of "as low as reasonably practicable" (ALARP) is applied (HSE 2001). This looks to provide a pragmatic and cost-effective way of providing protection. With premarket testing, it provides an assessment of the cost, time scale and intricacy of developing and producing a system to protect against all known hazards, and the level of protection to be applied. In development and validation testing every possible parameter could be tested and retested. This could take tens of millions of dollars or pounds and many years or decades, but is that reasonably practicable for the industry? Probably not. Thus a risk/benefit is applied to reduce the risk to the end user to ALARP.

To ensure that appropriate performance is achieved and that a rebreather design follows the ALARP principle, the system needs to be validated. As stated, this needs to be such that it supports the whole diving industry from manufacturer to end user. An auditable way of achieving this is to undertake validation testing and for the testing to be conducted and assessed by independent third parties.

MANUFACTURER CONSIDERATIONS

Safety

Most manufacturers and diving operators have a similar view of the whole concept of performance and testing. Manufacturers want to sell or provide the end user with a safe product; they do not want to sell something that is known to be dangerous.

By providing the user with a safe, quality product, manufacturers reduce their liabilities; in addition, a product known to be safe and reliable is also likely to increase their market share.

Commercial viability

There are obvious driving factors for all the manufacturers to produce a safe and reliable product, but from their perspective it also has to be commercially viable. As a result, in defining what testing to undertake it is essential to specify only what is actually required. Endurance testing is time consuming and can take many days to perform; for these and other tests a pragmatic approach that provides sufficient data to move forward is part of the consideration.

Test equipment is expensive. Many manufacturers have invested heavily in this equipment, they have to balance the cost of investment against the expected returns from sales. Reducing up-front testing costs will reflect on the market price.

Development and proving

During design and development, testing is used throughout the process to define and confirm the performance of a rebreather. The culmination of this is the testing required to place and maintain a design on the market. This falls into two broad categories for testing and certification:

- **Type testing.** Once a manufacturer has a piece of equipment they would like to take to market, it will be subjected to a series of validation tests (probably both in-house and by a third party). Type testing, usually with independent audit and certification, shows that that design will work as intended and is fit for purpose.

- **Quality-control testing.** If a manufacturer is going to make tens or thousands of units, they will have to undertake production quality tests. It is not acceptable to assume that as the first unit is acceptable all subsequent production units will be. It is possible that a slow degradation in quality and performance may occur during production of multiple units.

Complaints and incidents

An unfortunate aspect of rebreather testing is also the need to use it in the event of a failure or incident. Manufacturers can use testing for investigating complaints or to support incident investigations. If they have quality baseline premarket test and performance data, then if there is a complaint the performance of the unit involved can be determined and compared to show if there is a shortfall in performance.

TESTING PRINCIPLES

Conventional engineering

Rebreathers are used in harsh, extreme environments. Tests are required to ensure that mechanical strengths are adequate for the intended use and that the unit is well engineered. They also need to ensure that appropriate materials have been used and that those materials will not be unduly affected by the environmental conditions — for example, saltwater, cold, impact and abrasion.

Physiological

Testing, particularly from a respiratory-performance point of view, needs to be physiologically based. It needs to be cognizant of the physiological aspects that you are trying to support and verify. There is no point undertaking performance tests on a breathing circuit if it has no relevance to the person who is going to be using the unit.

Physiological-based testing can cover several areas: unmanned tests (Figure 1), controlled manned tests in tanks and chambers (Figure 2), and ergonomic, form, fit and function assessments. Physiological testing, as with many aspects of testing, needs to realize that compromise has to occur. A nominally perfect rebreather may be produced in respect of respiratory performance, but it may be impossible to wear and dive if, for example, you cannot reach and operate some of the controls.

Figure 1. Unmanned test chamber and breathing simulator.

Figure 2. Controlled manned testing in a dive tank using a cycle ergometer.

Consensus

In the development of rebreather test requirements, the whole industry should be involved. The outcome needs to be a pragmatic consensus that includes domain technical experts such as design engineers, diving physiologists and end users. They need to be able to provide input based on up-to-date technology, knowledge and appropriate best practice. It must also include the manufacturer's perspective: what to build, how to build it, what they can sell as well as input from test houses and accreditation agencies. There is no point in putting together testing requirements if a manufacturer cannot produce equipment that complies and test houses are unable to conduct the tests. Finally, it must consider what information end users will require — for example, endurance data — to successfully dive the equipment.

ALARP

In addition to applying the ALARP principle to the design of an apparatus, testing requirements should also be ALARP. The tests have to be something that a manufacturer can readily conduct or arrange and by an appropriate testing authority. The testing also has to be cost effective; it cannot cost 10 million dollars or pounds to test something that will be sold in small numbers for a few thousand dollars or pounds.

WHAT TO SPECIFY

Mechanical

The mechanical aspects of a diving rebreather are an essential starting point. Diving apparatus includes high-pressure gases, and it is imperative to ensure that their containment and control is appropriate. Thus, are all pressure components such as cylinders, hoses, pipes, regulators and gauges appropriate for their working pressure and to certified standards where appropriate? Similarly, if there are flexible pressure components such as hoses, are the end connections secure, and are they sufficiently flexible or rigid enough for the intended use?

The whole system will need to be built within a housing, frame or other support/containment. This needs to be strong enough for the intended purpose and have sufficient strength to secure the unit to the diver. Any carrying and lifting points should withstand, with an appropriate safety margin, expected forces that may be applied.

Materials

Linked with the use of high-pressure systems, many will also contain high partial pressures of oxygen; it is therefore essential that the design and materials used are compatible with high-pressure oxygen. By intent the equipment will be used in seawater and the marine environment. Are all materials appropriate to this environment? Will they corrode, or are there incompatible metals that may result in electrochemical degradation?

Diving equipment gets wet and may stay damp for extended periods. Will it degrade or just simply rot away? Often overlooked are the materials used in a mouthpiece or full-face mask. When a diver puts these on his face and/or in his mouth, will they be toxic or invoke an allergic reaction?

Breathing performance

The breathing performance of diving apparatus, particularly in respect to work of breathing (WOB) and respiratory

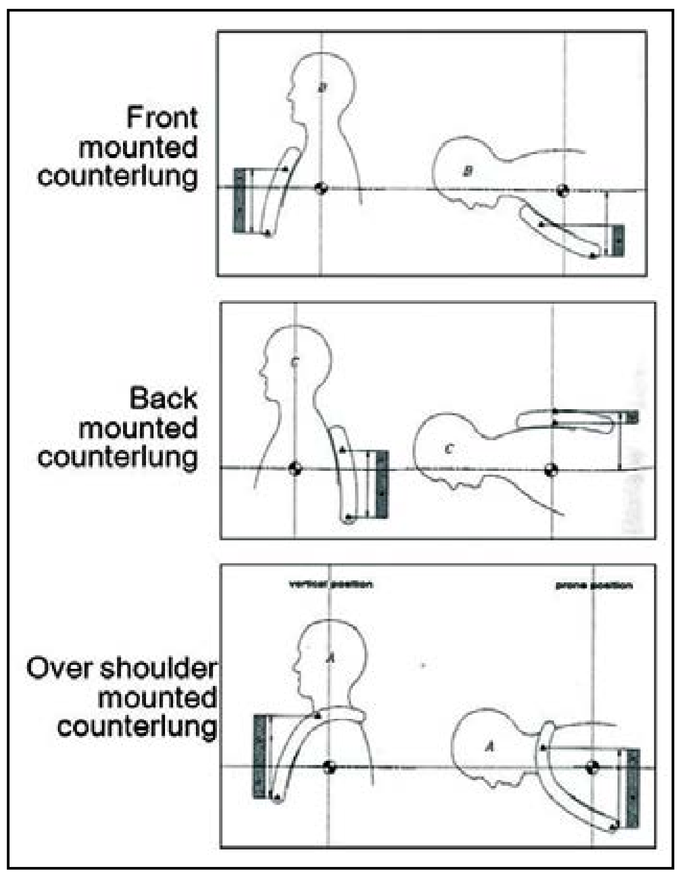

Figure 3. Hydrostatic imbalance.

pressure are the parameters known to most in the industry as the ones that need to be tested. Work over many years has helped define and revise these requirements, and significant safety advances have been made, although declared performance requirements often still do not reflect our current understanding of the physiological limits (Warkander, 2007). However, specific to rebreathers there additional limitations due to hydrostatic imbalance (Figure 3) that need to be addressed, and appropriate determination of respiratory pressure has been challenging physiologists and test houses for years. Some current standards (EN 14143, 2003) are inappropriately specifying peak-to-end respiratory pressures, which results in a double accounting. This is currently being addressed by determining the elastance of the system rather than a respiratory pressure per se (Figure 4) (NATO, 2011).

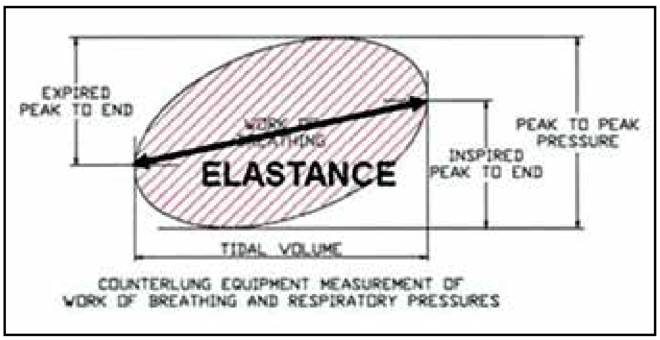

Figure 4. Rebreathing equipment WOB, respiratory pressures and elastance.

Gas control

The two gases that are actively controlled within a diving rebreather are carbon dioxide and oxygen; inappropriate control of either of these gases leads to one or more of the three H's (hypoxia, hyperoxia and hypercapnia), which are insidious hazards of rebreathers.

Inspired carbon-dioxide levels need to be specified in respect to volume weighted average inspired levels, i.e., the average partial pressure of carbon dioxide (PCO_2) in each breath, which reflects on the internal volume of a mouthpiece or oronasal mask and of any face-piece one-way valves. In addition, the performance and endurance of a carbon-dioxide removal system needs to be defined to the point that a known level of carbon dioxide is exhausting from the canister. There is obviously a link between these two parameters, and the interaction needs to be addressed.

Many rebreathers allow large variations in the inspired partial pressure of oxygen (PO_2), whereas others are designed to closely control the inspired level. Human physiology can tolerate a fairly wide range of inspired PO_2. However, to ensure that hypoxia or oxygen toxicity do not occur, or that the inspired levels are not out with those required for the decompression procedure being used, appropriate limits need to be applied, tested and verified. With the potential for large variations that are physiologically acceptable, there is a risk that overspecifying an acceptable tolerance may result in systems being unduly labeled as unacceptable for diving.

Environmental conditions

Rebreathers may be required to work over a large range of ambient temperatures. There are user groups who take rebreathers into the arctic under ice where they may be "frozen" on the surface and in subzero water on the dive. Conversely, they may also be used in the tropics where surface temperatures in strong sunlight may exceed 55°C (130°F) and water temperatures can be up to 36°C (97°F). In extreme cold many components may become rigid and brittle, and electrical systems may fail. At high temperatures the flexible components may become soft and at risk of failing at high pressure or allowing helium to leak out by penetrating through a hose material. Oxygen sensors and absorbent canister performance can be adversely affected at low temperatures with endurances in cold water greatly reduced (Figure 5).

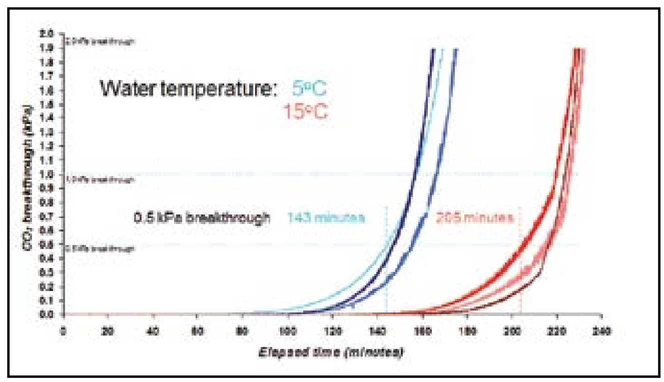

Figure 5. Reduction in absorbent canister endurance with a 10ºC (50°F) reduction in water temperature; n=3 runs at each temperature.

Ergonomic, form, fit and function

As indicated previously, there is no point producing a rebreather that has good technical performance if it is not practical in use. An essential series of tests are to undertake an ergonomic trial (also known as practical performance) on the form, fit and function of the system. This will range from ease of donning, doffing, ability to get into and out of the water, swimming and maneuverability. An essential part of this is also to ensure a diver can find, see and read any displays and similarly that they can readily find and operate any controls.

Labeling, marking and instructions for use

It may seem obvious, but a rebreather needs to be checked to see that it is labeled with essential information for the user such as sizing, any expiry date of limited-life components, maximum working pressures and, to cover product liability, who manufactured it and how to contact them. It is not practical to mark or label equipment with all information a user may require, but additional information can be included in instructions for use. Any instructions for use need to be checked to ensure they are comprehensible and provide essential safety information such as what absorbent to use, temperature and depth limitations, including equipment endurances.

An interesting aspect of marking a rebreather is to be able to demonstrate that it has been adequately premarket tested and validated; the current European standard for rebreathers EN14143 (2003) requires it to be "CE" marked to show which standards the rebreather and any components have been validated against and by who (Figure 6).

Figure 6. First-stage diving regulator showing CE marking.

FUNCTIONAL SAFETY

One of the overarching aspects of a rebreather to be assessed premarket is its functional safety. Rebreathers are a life-support system to allow a diver to enter and survive in a harsh alien environment; as such the whole system has a safety critical function. There several ways to assess the functional safety of a life-support system and a rebreather; to date this has primarily been undertaken by a failure mode effect and criticality assessment (FMECA). A current shortfall in this approach is that it has not defined what level of risk, failure or criticality is acceptable; these need to be defined to know the risk associated with using a system and thereby its overall functional safety.

To quantify a FMECA for a rebreather, a risk matrix (Table 1) may be used. This defines what the severity of the outcome of a failure would be (the rows on Table 1) and the likelihood of a failure resulting in that severity (the columns in Table 1). These risks are bounded by time (the likelihood applies to one year of use) and number of exposures (only one rebreather being used for the year).

This then allows for minor events, such as occasionally cutting a hand when operating a valve with a negligible outcome, being assessed as acceptable, to an improbable catastrophic event, that is, where several people may die if the cylinder on a dive boat explodes, being unacceptable.

This matrix is calibrated by considering that for the use of one rebreather for one year the likelihood of a critical event (defined as a single fatality) occurring is less than 1 in 10,000 to 1 in 100,000 (i.e., improbable). This is socially considered as an acceptable level of risk for an at-work activity. It is anticipated that this quantified FMECA principle will be applied in the future to assess the functional safety of diving rebreathers.

Table 1. Proposed risk matrix for assessing functional safety.

Severity	Likelihood (per year)					
	Frequent[a]	Probable	Occasional	Remote	Improbable	Incredible
	>0.1[b]	>0.01 and ≤0.1	>0.001 and ≤0.01	>0.0001 and ≤0.001	>0.00001 and ≤0.0001	≤0.000001
Catastrophic	Unacceptable risk	Unacceptable risk	Unacceptable risk	Unacceptable risk	Unacceptable risk	Acceptable risk
Critical	Unacceptable risk	Unacceptable risk	Unacceptable risk	Unacceptable risk	Acceptable risk	Acceptable risk
Major	Unacceptable risk	Unacceptable risk	Unacceptable risk	Acceptable risk	Acceptable risk	Acceptable risk
Marginal	Unacceptable risk	Unacceptable risk	Acceptable risk	Acceptable risk	Acceptable risk	Acceptable risk
Negligible	Unacceptable risk	Acceptable risk	Acceptable risk	Acceptable risk	Acceptable risk	Acceptable risk

[a] Quantitative likelihood category
[b] Likelihood of dangerous failure of any safety critical function (in a single re-breather per year)

PERFORMANCE STANDARDS

Diving apparatus standards

National and international standards for diving apparatus have been developed over many years. Probably the first international standard was an agreement between the U.S. Navy and the Royal Navy on how to test diving equipment (Middleton and Thalman, 1981). To resolve problems with diving fatalities in the North Sea, the UK Department of Energy and Norwegian Petroleum Directorate produced guidelines in 1984 (Nor Petro, 1984), which were updated in 1991 (Nor Petro, 1991). These guidelines have now been superseded by a Norwegian Standard for diving systems to be used in the Norwegian sector of the North Sea (Norsok U101) (1999). The U.S. NEDU has been a leader in the testing and assessment of diving equipment with the technical reports of 1994 (Tech Man, 1994) and more recently 2010 (Warkander, 2007) defining requirements. In a broader international sense, the military-diving communities from many nations have agreed to a standard for diving equipment (STANAG 1410) (NATO, 2011) that applies the most up-to-date physiological data on breathing performance standards.

Rebreather-specific standards

Most of the historical diving-equipment standards have defined, in a general sense, the respiratory aspects of underwater breathing apparatus, e.g., WOB, respiratory pressures and acceptable carbon-dioxide levels. What they did not do is provide a standard and test regime for all aspects of diving apparatus, including its practical use and function, or be specific to different types of apparatus. The current European standards for diving apparatus address the complete system and cover all of the aspects described in this paper. With EN 14143 (2003) being the only standard specifically for rebreathers and embodied in many nations' law, it is probably becoming a de facto world standard for diving rebreathers. Many nations in both the Northern and Southern Hemispheres are relating performance and requirements to those in EN14143. Also as there is a suite of European standards for diving apparatus and systems, these standards are able to pull together the requirements for many apparatus subsystems. For example, EN 14143 defines the performance of regulators, hoses and demand valves as specified in EN 250 (2000) and integrated buoyancy systems as per EN 1809 (1998).

Table 2. Categories of EU PPE

PPE Category	CE marking requirement	Example diving equipment
0	Excluded as PPE. Does not require marking.	Equipment for security, police or military applications
I	Self-certified CE marking by manufacturer.	Diving face masks
II	CE marking by notified body. Type testing only.	Diving suits
III	CE marking by notified body. Type testing and product quality control.	Diving breathing apparatus — e.g., rebreathers

EUROPEAN PPE DIRECTIVE

Principle and categorization

Diving apparatus is classified as personal protective equipment (PPE) and as such within the European Union (EU) it falls under the requirements of the PPE Directive, which is effectively part of European law. To many people, including those who reside in the EU, it is often difficult to understand the legal aspects and processes involved in applying the directive. However, they need to be mastered for equipment to be certified for sale within the EU.

In 1989 the EU issued the first PPE Directive 89/686/EEC, which over the next decade was amended by 93/95/EEC, 93/68/EEC, 96/58/EC and 98/37/EC. The outcome of the PPE directive and the subsequent amendments was to bring some clarity and classification to the requirements and performance of diving PPE. The simple requirement of diving and any other PPE is that it needs to be "fit for purpose."

PPE is classified at different levels according to the protection it is required to provide (Table 1).

Diving rebreathers are classified as category III PPE. This means that they not only have to be type approved (CE marked) but also to have thorough life product quality assessments. This accreditation may only be given by an approved notified body.

CE certification

There are two routes to achieve CE certification and for an equipment to be CE marked (Figure 6); for both of these you have to produce a technical file. This is a collection of documents and evidence that captures the detail of the design and the available test data defining the performance of the apparatus.

A notified body may certify a product as complying with the PPE directive based solely on the technical file, in which case it can be CE marked as per the directive.

A preferred route is for a product to meet the requirements of an EU standard that has been harmonized with the PPE directive, i.e., for rebreathers EN14143 (2003). In this case the technical file will contain evidence that the rebreather complies with the requirements of the standard, it may then be certified and marked as both complying with the directive and the harmonized standard (Figure 6). Equipment CE marked to a harmonized standard is then recognized as meeting minimum performance criteria.

WHERE AND WHO SHOULD TEST?

During development

During the design and development it is likely that manufacturers will conduct an extensive iterative series of in-house tests, although they may also choose to use specialist, independent test centers.

For certification

Before premarket release, the testing has to be overseen by an independent authority, the notified body. That could mean that the representative(s) from the notified body independently witness tests in house at a manufacturer or arrange for/accept tests conducted by a specialist, independent test center.

Who is competent?

Notified bodies for the assessment of PPE under the EU directive are appointed by the government of individual EU nations. The government is required to audit and confirm that the notified body is competent to undertake these assessments; typically this will be conducted by a national accreditation body.

Ideally test data will be provided by an independent test center that has also been nationally accredited. In reality, it is not cost effective for test centers to go through the process of accreditation for a small testing market such as diving equipment and rebreathers. Thus to find a test house with formal accreditation for diving rebreathers is almost impossible. However, a test house does need the appropriate facilities and expertise; test-house competence primarily comes from a track record and experience in developing and conducting the required tests. The NEDU, and other major test centers such as QinetiQ in the UK, have been doing this for nearly 40 years and have led the way in developing test procedures and expertise in the wider community.

SUMMARY

The European standard for rebreathers, EN14143 (2003), has been mentioned many times during the conference and is a key element of premarket testing. It is an international consensus standard but is not the ultimate requirement; it is the best that could be agreed upon at the time of writing. In its production the EU has endeavored to use the best information available from experts throughout the diving community; however, it contains many compromises and has elements that could be improved. Some organizations, such as the military in many countries, have more comprehensive assessments, particularly when it comes to manned performance and ergonomics.

As stated, EN14143 is harmonized with the EU PPE directive to define minimum requirements. It is fairly comprehensive with more than 50 separate requirements and tests, the testing covering pragmatic aspects of diving physiology, mechanical and material strengths, function safety and operation use. However, premarket testing places a significant burden on manufacturers to conduct tests and obtain accreditation; as a result, the requirements are constantly being revised.

The requirements for premarket testing need to be a consensus involving the whole diving industry; all interested parties, from manufacturers to end users, need to discuss and agree on the testing requirements that will make rebreather diving as safe as possible.

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PREMARKET TESTING: THE U.S. PERSPECTIVE

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WHAT IS DIVE LAB?

Dive Lab is a privately owned company started in 1997 as an equipment test facility and dealer training center facility in support of Kirby Morgan Diving Systems, Inc. (KMDSI) of Santa Maria, CA. Kirby Morgan is the world premier manufacturer of deep-sea diving helmets and full-face masks. Dive Lab provides engineering, testing and support services for KMDSI. Dive Lab is located in Panama City, FL, on five acres and has buildings with more than 23,000 ft^2 (2,137 m^2). Dive Lab has a state-of-the-art test facility equipped with breathing simulators and chambers having a 656 ft (200 m) test rating for breathing simulation as well as several pressure test chambers for testing large and small equipment to depths of 1,000 fsw (305 msw). Fabrication and machine shops include a CNC Plazma arc, lathes and mills, as well as a fiberglass shop for rapid prototyping and specialty manufacturing. Besides testing, Dive Lab oversees all KMDSI technician training and provides technician training maintenance and repair course on KMDSI and Dive Lab products to military, commercial, public safety and scientific diving communities.

WHAT DIVE LAB DOES

- It is a test and evaluation center for Kirby Morgan helmets, full-face masks, and products.
- Dive Lab provides developmental, engineering, and fabrication services primarily for Kirby Morgan Diving Systems as well as military and government agencies.
- Dive Lab oversees all official Kirby Morgan factory maintenance and repair training for Kirby Morgan dealers worldwide and for commercial diving schools, military, commercial diving contractors, independent divers, and diving technicians.
- It provides specialty manufacturing, including lightweight surface-supply systems and pressure/flow test systems for military and scientific use.
- It conducts a full range of scientific tests and studies in accordance with European Union (EU) standards as well as other national and international standards and requirements.

WHAT IS A CE MARK?

Some people say that CE stands for "Conformity Europe," while others say it means "Cash Extortion." The CE mark is similar in concept to the Underwriters Laboratory (UL) approval in the U.S. There are UL industry standards for electronics but not for diving equipment. Other than those of the U.S. Navy, there are no formal human breathing-performance standards for diving apparatus in the U.S. and only a few standards for components such as harness assemblies, diving umbilicals, and diver gas-supply systems. In Europe, standards have been established that require all diver-worn and support equipment meet basic breathing and performance standards as well as guidelines for equipment manufacturing. These standards include user guides, operations and maintenance manuals, failure mode, effect, and criticality analysis (FMECA), and engineering drawings. Surface-supply breathing apparatus and open- and closed-circuit scuba fall under the category of personal protective equipment (PPE). The CE mark does not guarantee the equipment is safe, just that it has gone through complex testing and review/audit of the manufacturer's quality-assurance (QA) program. The CE mark followed by the notified bodies identification number is displayed on the product once certification has been completed.

WHAT IS A NOTIFIED BODY?

For tests to be recognized as meeting CE test standards, they must be reviewed and approved by an EU-approved "notified body" that acts as the certifying authority and verifies that all testing was conducted properly and in accordance with the applicable standards and the review of all drawings, manuals and documentation met all applicable requirements. A notified body is appointed by the government of an EU country, normally through the trade ministry. The notified body may or may not be expert in the design and use of the particular equipment or in the interpretation of the particular standard(s) that apply. This is where the manufacturer needs to push to make sure the tests are done correctly. For example, when Dive Lab started CE testing in 2001, our notified body wanted to test at their facility in Europe, not ours, even though we had better equipment and capabilities. We finally ended up switching to another notified body that was willing to come to Dive Lab, and testing worked well. The notified body that

Figure 1. Dive Lab, Inc. Photo courtesy Dive Lab.

Dive Lab works with was required to get approval from the Ministry of Trade so Dive Lab could be recognized by them to conduct CE testing for Kirby Morgan products as witnessed by the notified body. Currently there are no U.S.-based notified bodies for diving equipment.

Selecting a notified body that has experience with diving equipment is essential if testing is to be conducted properly. Because the diving industry is so small and there are few actual test facilities, the notified body may go to various equipment manufacturers with test equipment to have them conduct tests on their behalf. In some cases, one company may actually test their competitor's equipment. Not all notified bodies do things the same way, and many are not knowledgeable about diving equipment, especially rebreathers.

Notified bodies have latitude to interpret standards and do not all work in the same manner and will often insist on yearly intensive and expensive audits that also include equipment retesting. While all manufacturers of rebreathers and respiratory equipment are required to be audited yearly, this might only entail an audit of the manufacturing, material control, and process procedures, or it could be a lot more. Test facilities are subject to inspections that include verification of calibration records for gages, measuring instruments, calibration gases, and test equipment as well as demonstration of testing knowledge and procedures. In addition, the test house will usually be required to demonstrate specific capabilities.

Companies must have all new equipment tested to the applicable EU standards before they can sell in Europe. In addition, they must undergo retesting of some products each year. Having to retest things such as the field of vision of a mask when absolutely nothing has changed or having to do CO_2 washout tests on a full-face mask that has been tested four years in a row and has never even come close to failing, or having to complete cold and hot storage tests when nothing has physically changed, can be a little frustrating. This is where the cash extortion part comes in. CE costs "BIG BUCKS," and the notified body can interpret the standards and requirements with great latitude. Companies that are certified ISO 9000 have an easier time with the audits, which should cost less because the annual ISO audit covers most of the manufacturing process and quality control but not necessarily testing. For a U.S. manufacturer, finding a good overseas test facility such as the ANSTI facility in Fareham, UK, run by Ian Himmens and Stan Ellis, can save U.S. manufacturers time and money for appropriate testing. (See http://www.divelab.com/assets/pdf/technical/Regulator_Performance.pdf.) Testing is extremely important, and at the moment the EU standards are the most comprehensive and best guidelines to use. Even if a manufacturer chooses not to sell in the EU, the EU standards will help ensure that products meet recognized standards.

Figure 2a. Open-circuit band mask in ANSTI test chamber. Photo courtesy Dive Lab.

Figure 2b. Mk 16 closed-circuit rebreather in ANSTI test chamber. Photo courtesy Dive Lab.

Figure 3. Field-of-vision test on a helmet. Photo courtesy Dive Lab.

WHAT IS CE TESTING?

Gaining a CE mark on a breathing apparatus is complex, expensive, and involves significant paperwork. Setting up and operating a competent test facility is costly, and few manufacture have the knowledge and experience to run tests, not to mention cost for all the test equipment. Setting up a rebreather test facility can easily exceed a million dollars as a fully capable breathing simulator can cost more than a hospital magnetic resonance imaging (MRI) test setup. Testing and certifying diving equipment is not profitable for an independent lab, but with CE regulations every new piece of equipment has to get tested and the paperwork trail has to be assembled.

Notified bodies visit manufacturers to audit QA procedures, operations and maintenance manuals, FMECA procedures, calibration records, and technical documentation. This normally happens before witnessing performance and functional tests to ensure the equipment has the proper paper trail. If everything is correct, and the equipment meets the requirements, they award the CE mark to the newly tested equipment. Dive Lab's notified body usually brings at least two people for an annual 10-day audit, and the expense can be brutal. Audits can include verification testing of CO_2 washout, hydrostatic and imbalance testing, hot and cold storage, overpressure, and others. (See Appendix 1 for more detail.) Pretesting may be required months in advance before a CE audit and repeat testing to compare results with the notified body present. If the documentation is good, and testing is good, everyone is happy.

TESTING IN THE U.S. AND EU

In the United States the diving equipment industry is largely self-regulated, and there is little government intervention until something goes wrong. The Occupational Safety and Health Administration (OSHA) regulates commercial diving and diving instructors, but there are little to no manufacturing or performance standards for scuba regulators, rebreathers, diving helmets, or full-face masks. As mentioned, the sale of diving equipment in the EU requires a CE mark in compliance with the harmonized manufacturing and testing standards, and the product manufacturer bears sole responsibility for obtaining the CE mark. Selling equipment in Europe without a CE mark would incur a dangerous liability hazard. Accordingly, most of the large scuba equipment companies are based overseas to more easily conform and deal with EU requirements. Diving-equipment manufacturers in the U.S. must go through the CE process to market their products in countries where EU compliance is required, and this puts U.S. manufacturers at a significant competitive disadvantage. Dive Lab's notified body had to get approval from the Ministry of Trade before Dive Lab could conduct CE testing of Kirby Morgan products. The testing has to be witnessed by the notified body.

DIVING-EQUIPMENT STANDARDS: PRESENT AND FUTURE

EU standards are established by technical committees whose appointees may or may not be knowledgeable in the equipment and/or may not attend all the meetings during the establishment of the standard. Committee members draft the minimum safety standards for products and equipment to be sold and freely moved within the EU. Gavin Anthony and Ian Himmens, who both attended RF3, have been helpful to Dive Lab in interpreting the not-always-clear wording of the standards. Unfortunately, no Yanks are allowed on the diving committees because the U.S. is not part of the EU. Typically, the standards are made by persons within the industry who have a vested interest. As an example, Kirby Morgan tried to get a person on the committee that was being drafted for surface-supplied diving equipment. Kirby Morgan was not allowed on despite their expertise and experience in surface-supplied diving and the fact that they manufacture 90 percent of the commercial diving helmets sold worldwide.

Does it seem that I have a love-hate attitude with the EU diving standards and the CE mark? Yes, I do. EU standards are a great idea for improving diving safety, but the process could be improved. In addition to allowing visiting experts from non-EU countries to sit on standards committees, I believe the standards system would benefit by providing historical sources to give them context. For example, parts of some standards are drawn from others without proper reference or clarity as to breadth of coverage. The future of diving standards and test facilities in the U.S. is uncertain, and this is not good for the diving industry. I believe industry-driven standards are better than government-dictated standards. If we do not adopt sound industry standards in the U.S. or at least team with groups that have standards, change could be forced from government agencies that would be intolerable for most manufactures.

APPENDIX 1

COMMENTS ON CE TESTING PROCEDURES

Basic rebreather design. One of the most important items that must be completed before any manufacturer can bring a rebreather to market is a failure mode, effect, and criticality analysis (FMECA). FMECA outlines all components that could fail and identifies the type of failure, the probability, and severity as well as possible causes of the failure and mitigation and emergency procedures.

Strength of materials. This includes a basic assessment of overall materials to ensure they will not be affected by saltwater, cleaning compounds and general wear and tear. Components shall not have sharp edges or points where the user or the equipment could be damaged. There is a lot to be considered in the selection of materials to be sure they remain durable after being subjected to wear and tear as well as cleanings and exposure to the elements.

Pressure vessel and valve requirements. Basic requirements placed on the pressure vessel being used with rebreathers and emergency systems must meet all applicable national standards for pressure vessels, much like the U.S. Department of Transportation (DOT) requirements.

High- and medium-pressure parts and connections. There are basic tests that must be performed to all low-, medium- and high-pressure components, and some of them are destructive. Many tests can be done by the manufacturer before having the test house/facility do it. Items such as metallic high- and medium-pressure tubes, valves and couplings shall be capable of withstanding a pressure 50 percent greater than the working pressure of the pressure vessel. Non-metallic high- and medium-pressure tubes, valves and couplings shall be tested to prove that they are capable of withstanding a pressure of twice the rated working pressure of the pressure vessel. Companies that are capable of manufacturing these parts can at least pretest before actual CE testing. Hoses and fittings shall be set up so that it is not possible to connect a low- or medium-pressure hose assembly to a high-pressure outlet or connection or one type of gas system to another type. Other tests include a breathing bag burst pressure test demonstrating that the breathing bag can withstand an internal pressure of 300 mbar (4.4 psi) for one minute, a volume breathing bag test showing a minimum floodable volume of 4.5 L, and an overpressure relief test that shows the maximum internal breathing loop pressure will not exceed 40 mbar (0.6 psi). Exhaust routing valve tests must show that the dive surface routing valves are adequate. There are other more complex tests such as an oxygen surge test that requires specialty test equipment to complete it safely and properly. It is my opinion that any manufacturer that has the ability to design and manufacture an open- or closed-circuit rebreather should also have the ability to do preliminary testing before going to the approved test house.

Electromagnetic test. The apparatus shall be tested in accordance with EN 61000-6-1 with imposed electromagnetic field frequencies in the range 80-1000 MHz. This test is to make sure the electronics do not have frequency interference problems such as radio interference from simple items such as cell phones or transmitter devices such as underwater transducers. To understand it, you must get into EN61000-6-1 standard. This type of testing requires special equipment.

Hot and cold storage tests. Hot and cold storage tests expose the underwater breathing apparatus (UBA) to extreme temperatures to see if it suffers damage or loss of performance. These tests are usually done before all the other tests to stress the equipment. For the cold storage test, the fully predived and calibrated UBA is placed in a finely controlled freezer. Before this test the apparatus shall, where required, be calibrated and shall be breathed for a period of five minutes and then stored first at -30°C (-22°F) and then at 70°C (158°F) for not less than three hours before removal and allowed to return to room temperature. Then switch on the apparatus and calibrate if required; place the UBA in the test tank, and test it at a pressure of 1.0 bar at a ventilation rate of 40 $L \cdot min^{-1}$ using an oxygen consumption of 1.78 $L \cdot min^{-1}$ for the duration of the apparatus as specified in the manufacturer's information. Performance should remain within the specified limits. The same test is repeated after storage at 70°C (158°F). There is little guidance of how to do these tests or what constitutes pass or fail, so I have introduced my interpretation.

Resistive effort performance requirements. Breathing performance testing for rebreathers is similar to open-circuit CE testing in accordance with EN-250. Known as resistive effort or work of breathing (WOB) testing, a mechanical breathing machine draws a fixed volume of gas from the item being breathed and pushes out the same volume. During inhalation and exhalation cycles, a linear transducer (extremely accurate length measuring instrument) measures the volume of gas being moved, while an extremely sensitive pressure transducer records pressure samples at a rate of 1,000 samples per second. When a computer plots pressure against volume, the breathing loop is born. The maximum inhalation pressure allowed is -25 mbar (-0.4 psi), and the maximum exhalation pressure is +25 mbar. The pressure values are converted to a work unit known as Joules/liter. The formula for maximum WOB for the EU standards is WOB = 0.5 + (0.03 x RMV). For example, the maximum WOB for a work rate of 40 respiratory minute volume (RMV) is 0.5 + (0.03 x 40) = 1.7 $J \cdot L^{-1}$. The only requirement for an open-circuit scuba regulator is that it meet WOB at the single extreme rate of 62.5 RMV. For rebreathers, however, testing must be done using the gas mixture that would be used at the maximum depth stated by the manufacturer at 10, 22.5, 40, 62.5 and 75 RMV to depths of 165 fsw (50 msw) with nitrogen-oxygen and with appropriate helium-oxygen to a maximum depth of 358 fsw (109 msw) or a lesser maximum depth if specified by the manufacturer.

Hydrostatic imbalance tests. Hydrostatic imbalance tests measure peak inhalation and exhalation pressures with the rebreather in various physical attitudes a diver might assume. It is not an exact science, and test houses and notified bodies may differ in methods and interpretation. Peak respiratory pressures are measured with zero roll with pitches of 0°, -45°, -90° to +45°, +90°, +180°. The key to the test is finding the best starting point to zero the oral pressure, and rotate through all the positions. Many factors can alter the results for this particular test.

Carbon-dioxide absorbent canister. The endurance of the charged carbon-dioxide absorbent canister is checked in water at 4°C and -1°C (39°F and 30°F) as stated by the manufacturer for each specified absorbent material. The end-inspiration CO_2 partial pressure must remain at less than 5.0 mbar (0.1 psi) for the stated endurance. Canister duration testing can be extremely time consuming and require numerous tests to find fairly reliable canister duration times. Canisters must be tested with each brand of absorbent material.

Other items for test and documentation. (See EU standard for complete guidance.)
Gas control/supply system
PO_2 control
Setpoint maintenance at 40 RMV
Display
Gas endurance
Requirements for hoses, tensile strength, flexibility, burst and leak testing

Safety devices/pressure indication
Visual indication (appropriate for color blind)
Gages for each supply gas vessel
Ease of use
Appropriate range
Tests for hoses
Flow restriction
Range, scale and accuracy
Safety relief with a minimum flow of 300 $L \cdot min^{-1}$
Active warning
PO_2 monitor
Accuracy
Response time
Alarm
PCO_2 monitor

Ancillary
Face mask /full-face mask
Donning, doffing
Face-piece connections
Strap/face-piece pull testing deformation
Visor impact testing
Face mask field-of-vision testing
Body harness
Reliability, no single action doffing
Does not impair movement
Will not come off accidently
Adjustability
Cleaning and disinfecting
Recommended solutions and immersion times
Seawater resistance
Practical performance
Manned dives

PUBLIC DISCUSSION

JILL HEINERTH: I guess the elephant in the room is that we have units in North America that have been tested and are being sold. Our consumer base is uninformed, does not understand testing and is buying units because they felt good in the swimming pool. Test results by many manufacturers are not reported, and there is no standardized reporting format. What is more, the Internet describes feats of survival that are far beyond CE tests. I would love to see every manufacturer report their test results in a common format as you see when buying a car. What do you think the consumer needs to know? What should a manufacturer put on their website for someone who is interested in buying a rebreather?

GAVIN ANTHONY: A consumer needs to have confidence that the unit is safe and is fit for the purpose of its planned use. The consumer also needs enough hard numbers, such as canister endurance, to plan a safe operation. This information should be available in a common format that allows manufacturers' products to be compared to each other and to the European standard. But a little knowledge might be too much. Some tests, such as work of breathing (1.9 $J \cdot L^{-1}$), for example, could be hard for divers to understand and might be used incorrectly. Common information formats should be designed for the average diver, not just those with detailed knowledge of physiology.

HEINERTH: Can I take that as an endorsement that manufacturers should post their data on canister endurance according to the CE standard as opposed to reporting non-standard tests that are difficult to compare with other manufacturers?

ANTHONY: Yes, you should be able to compare apples with apples, but if a manufacturer wants to conduct additional tests, that is up to them.

MARK CANEY: The 14143 European standard is well known and seems to serve its purpose within Europe. It is understandable that non-European manufacturers are reluctant to embrace it because they had no input. Would there be any merit in considering developing an ISO standard using this as a basis?

MIKE WARD: I am not involved in writing the standards and have a lot of frustration. They are working on ISO standards for diving. The current European standard, 14143, covers everything and is probably the best available right now, although there are aspects I do not agree with. It is still a good standard. The United States needs to consider it carefully because it exceeds anything the military has and is comprehensive — not just for rebreathers but also for scuba and surface-supply diving. I am in favor of using the EU standard, and as it evolves into an ISO standard, it should get better.

ANTHONY: The European standards community debated whether to transfer the standard to ISO but decided to keep it within Europe. It is a nightmare just getting Europeans to agree, and while three international meetings a year in Berlin, Paris, and London are possible, going to Tokyo, Sidney, Rio, Washington, etc., would drive up the costs. If there is a push from outside Europe to move to ISO, that could occur but would be costly and time consuming.

CANEY: Having attended many European standard meetings, I would agree that there are different cultures.

MARTEN SILVANIUS: We are a test house for the European standard 14143. What challenges do you see with decision making for it, and what improvements could there be? There are a couple of years between every revision.

ANTHONY: How can we improve? I think Mark Caney almost has the answer. There is something of a north-south divide within Europe. Northern Europe is cold-water diving, and southern Europe is the warm-water Mediterranean. Getting compromise between them takes time that will be difficult to accelerate.

SILVANIUS: You do not think it is possible to improve on this?

ANTHONY: Not to speed it up, no, unfortunately.

UNIDENTIFIED SPEAKER: Gavin, you showed a risk matrix in which one incident in 10,000 was acceptable incidents. Was that in 10,000 dives or 10,000 units produced?

ANTHONY: The denominator is one rebreather for one year, but the unknown factor is how many dives on rebreather will do — one, 1,000? It is logical that one rebreather might be used for two or three dives every weekend or about 150 dives per year.

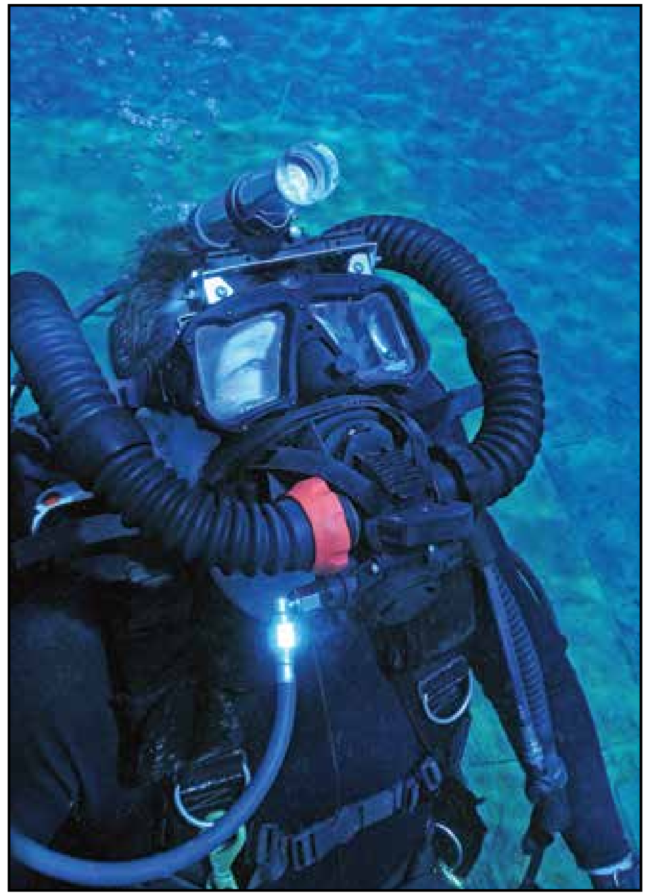
UNIDENTIFIED SPEAKER: That would produce one fatality in 10,000 uses?

ANTHONY: It is just a measure of probability. So, for a single rebreather it would have to be used for many years. Or you could have more than one rebreather used for one year.

LEON SCAMMERHORN: Having gone through the CE process with the Megladon and being the only American company to hold a CE on a U.S. CCR, I can say it is a very rigorous test and does prove fit for purpose, but it does not prove the diver is fit for purpose. I feel the standard should also be ISO, which requires you to be an ISO company. ISO is a quality-assurance tool for which you are audited once or twice a year, and that is important for turning around the safety culture in the U.S. and North America. One of RESA's goals is that every manufacturer should prove their products are fit for purpose. To join RESA, you have to prove your product has met some basic standards for work of breathing, scrubber duration, hydrostatic lung loading, etc. RESA members are CE marked or have proven their products have had third-party testing. The dive industry in the U.S. should adopt the 14143 harmonized standard as proving their rebreathers are fit for purpose. Open-circuit divers can find the CE mark on their regulators, and the same should apply to rebreathers. Look for the CE mark that proves the standard has been met. It is a great standard.

Dive Lab oxygen rebreather for submarine rescue use. Photo courtesy Dive Lab.

Dive Lab six-man CO_2 scrubber for submarine rescue use. Photo courtesy Dive Lab.



Kirby Morgan M-48 Mod -1 mask with open-circuit switch-over pod. Photo courtesy Dive Lab.

POST-INCIDENT INVESTIGATIONS OF REBREATHERS FOR UNDERWATER DIVING

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ABSTRACT

The most common methods of equipment testing in rebreather incidents are presented and discussed; these include equipment examination, scrubber testing, oxygen consumption tests, etc. During the last 10 years (2001-2011) there have been five rebreather-related fatalities in the Scandinavian countries, making up about 6 percent of the total diving-related fatalities. In total, 10 incidents involving 12 injured or deceased rebreather divers have been investigated. Applying a root-cause analysis to the incidents reveal that equipment problems were the trigger in seven of 12 incidents, whereas only one was triggered by buoyancy issues and four had an unknown trigger. Despite the large number of equipment problems, there were no equipment failures discovered in the investigated incidents highlighting the difficulty of human-machine interaction

Keywords: accident, drowning, fatality, forensic, hypercapnia, hyperoxia, hypoxia, mishap

BACKGROUND

Accident investigations in Sweden — background

The rules pertaining to accident investigations are largely determined by the local legal system. Thus, Swedish, or perhaps Scandinavian, post-incident investigations may differ from investigations in other countries, but it is hoped there will be some generic conclusions to be drawn from this paper.

In Sweden, accident investigations are almost exclusively carried out by the police or other official agencies. Once a fatal accident has been deemed not to involve any criminal activity, it is possible for a private citizen to carry out an investigation, but there is not much financial benefit from such an action since the law-courts usually award only minor damages.

The police authorities are mainly focused on excluding criminal activity. Second, the authorities are interested in consumer safety or workers health-type investigations where it would be more of a state against the “accused” litigation. For the latter two fields, there are agencies to survey the jurisdiction and in some cases commence investigations when considered necessary, as general consumer safety or worker health-type investigations do not need to be motivated by a prior accident.

In the case of a fatal dive accident, the police own the investigation in the sense that the authorities will decide how, when and what to investigate. The Swedish Armed Forces, Diving and Naval Medicine Centre (DNC) are at this stage only an advisory authority. The standard procedure in a fatal accident is to send the body to the morgue for a forensic autopsy, while the equipment, upon the invitation of the police authorities, is examined by the DNC.

Any rebreather incident in a military or commercial setting would also lead to a complete and thorough investigation directed by either the Armed Forces or the Work Environment Authority. Apart from this, in case of a large accident where many people (five or more) are killed or seriously injured, the Swedish Accident Investigation Authority (SHK) will investigate. In some instances the number of injured persons needed to start an investigation could be considered cumulative; this has resulted in the accident investigation authority commencing two investigations regarding recreational diving.

In 1997 mixed-gas diving and overhead penetrations were catching on, and there was concern from the surveying authorities that this would lead to an increase in accidents (Lundström et al., 2002). For this reason, an investigation was carried out regarding a non-lethal accident in which two divers breathing nitrox lost contact and orientation inside a wreck. This broad investigation was useful for the governing agencies but specifically concluded that the divers would not have been separated if they had used a buddy line.

In 2003 there likewise was a growing concern that the standard among recreational dive schools and instructors had been lowered and that this had caused an increase in incidents, leading to an investigation of an accident with one fatality and three injuries on a combined dive trip and dive course (Rosvall and Kjellberg, 2005). Apart from the obvious conclusion that the organizing company had shortcomings in their safety system and operational routines, the investigation led to a series of recommendations to the governing authorities, such as helping the consumer agency in creating routines and supervisory control of recreational dive education and pointing toward communication and coordination problems as well as education and equipment deficits in the rescue operation itself.

The EU and the Swedish system of accident investigation
Sweden has been a member of the European Union since 1995. Among the member states, a majority of the administrative laws and regulations originate in directives from the EU. The EU Commission tables directives for different fields. For diving equipment, it is the directive of personal protective equipment that regulates the basic requirements a product has to comply with to get a CE mark. The CE mark is a mandatory conformity mark indicating that the product is allowed to be traded freely within the European Union, and no member nation is allowed to put bars on that trade. In the directive, the products are categorized depending on the effect of a malfunction. Breathing apparatus for underwater use is a category III product, meaning that failures are potentially lethal. To get a CE mark on a category III product, an independent test house, designated by a notified conformity assessment body (notified body), has to declare that it is compliant with the directive. If it is a new product, the notified body would try to interpret the directive to figure out what tests to perform. To simplify that process, the European standardization institute creates working groups consisting of representatives from manufacturers, users, test houses, scientists, and governing authorities who negotiate a standard harmonized to the directive. In the case of rebreathers for underwater use, the EN14143-2003 is the harmonized standard. If a notified body finds that a product is compliant with the standard, the product then automatically is compliant with the directive. When giving out the CE mark, the notified body to some extent assumes responsibility for the product. Because of this assumed responsibility and the mere existence of an EU standard, accident investigations often end up showing whether the systems comply with the standard or not.

METHODS

Postmortem examination
The postmortem examination is obviously important, but one has to be aware of its limitations. A diagnosis of death by drowning is often a diagnosis by exclusion and does not capture the triggering event (Caruso, 2003). Unfortunately, there have been cases where it was stated that because the postmortem examiner determined the cause of death to be drowning, there was no need to carry out an equipment investigation.

Comparing open-circuit to rebreather incidents, three risk factors appear much more common in rebreather diving: hypercapnia, hyperoxia and hypoxia (Vann et al., 2007). None of those leave any traceable evidence that can be discovered in a postmortem examination (P. Krantz, pers comm 2012). Despite these limitations, the postmortem examination is very important and can find evidence of injuries that are hard or impossible to find otherwise, including air embolism, venomous stings and bites, and other medical issues (Caruso, 2003). In a case investigated by the Swedish police, a diver passed out on the surface and drowned. The original assumption was that the fatality was caused by hypoxia or hypercapnia, but the investigator did not settle for this and later found mention of allergies in the diver's health declaration. A subsequent search of the dive boat found allergenic agents (nuts). Because of this, the postmortem examiner reopened the case months after the initial examination and discovered large amounts of histamines in the stored blood. The investigation later concluded that an anaphylactic shock could have been the disabling injury (P. Krantz, pers comm, 2012).

Another issue where the postmortem examination is absolutely vital to establish evidence is in carbon-monoxide (CO) poisoning. In open-circuit incidents, it is easy to estimate the exposure based on a gas analysis from the cylinder and the depth of the dive, but with rebreathers it is much more difficult. The lung and the body tissues are very efficient scrubbers of carbon monoxide, so every time the gas is being breathed it is essentially scrubbed of CO (Forster et al., 1954). Determining the exposure then depends on how much gas was added from the contaminated source. If the source is the diluent tank, the CO exposure depends on the dive profile. If the CO is in the oxygen, it depends mainly on the workload and metabolism. In a semiclosed unit, the CO exposure will also depend on the workings of the dosage mechanism. Either way, to render the same exposure as in an open-circuit dive apparatus, higher concentrations are needed with rebreathers. The postmortem examination is an efficient tool at establishing incontestable evidence for CO poisoning besides examination of the gas content.

Rebreather equipment examinations and tests
An equipment investigation by the Swedish Armed Forces is conducted according to an established routine and checklist. It begins with the inquiry from the police, the information retrieval, the material and document handling, the investigation, and finally how the documentation and report are to be drawn up. The checklist is a memory aid to make sure nothing major is forgotten. It also stipulates a preinvestigation review where it is decided what tests should be conducted so that all parties involved have a common understanding. Details of the quality management system are described in a handbook that is required for preserving accreditation according to European laboratory standards.

What tests could and should be conducted depends largely on the condition of the unit and the specifics of the case. A broad outline is as follows.

One starts with downloading the logs from dive computers and/or the breathing apparatus according to the manufacturer's guide. The importance of this information cannot be overestimated. The dive unit's exterior is checked, and the gas content of the counterlung is analyzed. Analyzing the counterlung gas is in theory an analysis of the final breath, but in reality there are so many opportunities for the gas to diffuse and equilibrate with the surroundings as well as leaks from the cylinders that it is hard to unravel the true content of the final breath. If the finding is a lower oxygen fraction than both the cylinder and air, it might indicate hypoxia if nothing else has consumed the oxygen. Inspection of the cylinders and analysis of the gas is followed by inspection of the regulator and check valves. The rebreather is then connected to a breathing machine where work of breathing is measured and a CO_2 challenge and O_2 consumption test is conducted. These tests are followed by dismantling the unit and checking the sensors, electronics, batteries, absorber, and other parts. The unit is disinfected and assembled for a practical performance dive. This reveals those subtle things that are hard to pick up in unmanned testing, for instance, weight distribution, buoyancy, and leaks in certain orientations. Many units are user modified, and this is a good opportunity to check ergonomics and other implications of the modifications. Throughout the whole investigation, camera documentation is vital.

Figure 1. The ANSTI Life-Support Equipment Test Facility set up for measurement of breathing mechanics, scrubber capacity, and oxygen control in open- and closed-circuit breathing apparatus to a depth of 200 msw (656 fsw).

Scrubber testing

The standard test for CO_2 scrubbers is to use a breathing machine, usually the ANSTI or metabolic simulator (MetSim) (Figures 1 and 2), with a ventilation of 40 $L{\cdot}min^{-1}$ and addition of 1.6 $L{\cdot}min^{-1}$ CO_2 to the loop gas, during which the CO_2 level in the inhalation hose is monitored. The standard test could give an indication if the scrubber is spent or if there is a bypass issue, but great care has to be taken in the interpretation of the results since there is a risk of both false positives and false negatives. For instance, settling and thus CO_2 bypass, which might not have been present during the dive, can occur due to shaking during transport. Also, flooding during the incident or recovery may have reduced the scrubber's ability to absorb carbon dioxide. On the other hand, in a scrubber that has been left for a long period, the CO_2 bound to the surface of the absorbent will have time to migrate into the pellets that will give a spent CO_2 cartridge increased absorptive capacity that was not present during the dive (Arfert and Örnhagen, 1990). Another method that is not prone to these problems is a carbonate analysis. One takes a few samples from the inlet, middle, and end of the scrubber and analyzes the relative carbonate content. This shows where the reaction front is and determines the remaining scrubber capacity. The problem with carbonate analysis is that the unit has to be disassembled, and in doing so one might miss a problem such as a leaking seal, gasket, or settling that caused gas to bypass the scrubber instead of being spent.

To address these issues, we recommend starting with a breathing machine challenge. If the scrubber endures 20 minutes

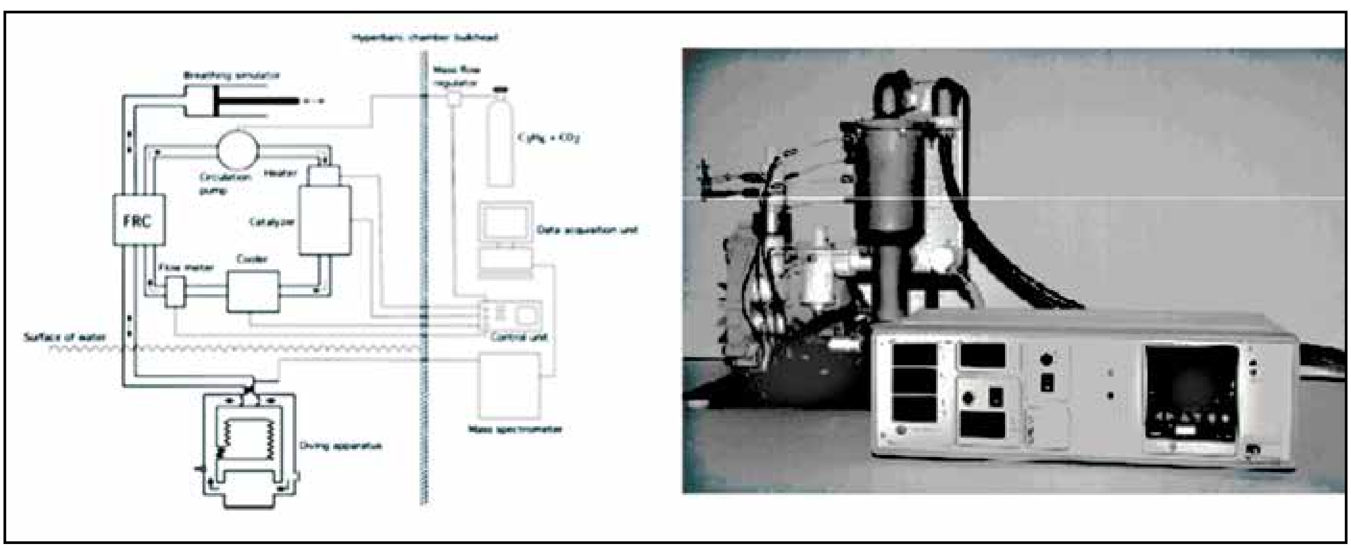

Figure 2. The metabolic simulator "MetSim" used for tests of oxygen consumption and carbon-dioxide scrubbing. The MetSim is particularly useful during dynamic situations such as pressure changes or sudden changes in oxygen consumption.

without a breakthrough, it is concluded that the scrubber was working. If there is an immediate breakthrough, we suggest to disassemble the unit, paying specific attention to sealing problems, and then do a carbonate analysis.

Oxygen consumption tests

For most of the unmanned testing, DNC uses an ANSTI Life-Support Equipment Test Facility (Figure 1). For metabolic testing, it uses the common inert gas exchange method in which oxygen consumption is simulated by extracting gas from the breathing circuit and injecting an appropriate amount of inert gas (NEDU, 1994). Thus, to simulate one liter of oxygen consumption when the loop oxygen fraction is 10 percent, one extracts 10 standard liters of loop gas (standard conditions are 0°C [32°F] and 1 bar [100 kPa]), which contains one standard liter of oxygen. To maintain the loop volume at expected levels, 9.0 standard liters of inert gas are injected back into the circuit. This method is good for steady-state situations, but we have found it problematic in dynamic situations, such as during rapid pressure changes or close to the surface, when it is hard to get the flows correct. This is especially a problem when testing closed-circuit rebreathers where slight differences in gas flows can change the loop volume.

For dynamic simulations, MetSim is utilized (Loncar and Örnhagen, 1997). This machine is shown in Figure 2. To simulate oxygen consumption, propane gas is injected into the breathing loop. The propane is then combusted in a catalytic converter, consuming oxygen while producing carbon dioxide and water vapor. Since no inert gas is added, there is no loop volume drift, and it is easy to simulate dynamic parts of a dive such as fast descents and ascents.

The oxygen setpoint control is one of the core technologies in rebreathers. During an oxygen consumption test, oxygen delivery can be studied at a system level, but one should also look at the function of the handset, alarms, etc.

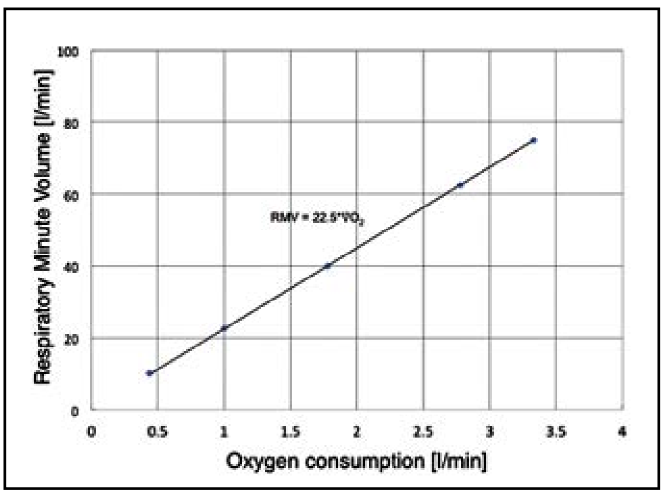

Figure 3. A plot of the ventilation and corresponding oxygen consumption as given by the rebreather standard EN 1414-3, 2003.

When doing these tests, it is good practice to use the standard test conditions, but these standard tests are generic, and an incident is specific, so a test at the incident depth or according to the dive profile often holds more information than a test at a standard depth. It is also often more revealing to use an oxygen consumption closer to the actual consumption of the diver.

When testing a ventilatory keyed unit (sometimes referred to as passive or demand-controlled rebreather), it is of utmost importance to understand how the specific dosing mechanism works. For example, ventilation versus oxygen consumption in the EU standard is a straight line with the slope of 22.5 L of ventilation to every liter of oxygen consumed (Figure 3). From the literature, it is obvious that this relationship varies greatly in humans (Morrison and Reimers, 1982).

Oxygen sensors

When there is an obvious physical problem such as broken wiring, it is easy to find a faulty cell, but otherwise it can be hard. A sensor that works in the lab is by no means proof that it worked during an incident. A typical example of this is when the sensor face was blocked during the incident, but the blockage later resolved. In one such incident, moisture had built up on the sensor face, effectively freezing the sensor signal during the incident. Fortunately, this could be detected in the onboard computer logs.

On the other hand, it is equally hard if a sensor fails in the lab to be certain that it was faulty during an incident. Rebreather oxygen sensors contain atomic lead that is oxidized during the sensor life. If the amount of free lead is reduced below a certain level, the sensor is not capable of showing high oxygen levels. Over time the maximum possible oxygen partial pressure a sensor can show is slowly reduced, making the sensor nonlinear at high oxygen partial pressures. If this nonlinearity occurs below the rebreather setpoint, there can be a substantial risk of oxygen toxicity. But because of the time between an incident and testing and because sensors are often kept in the rebreather in a high oxygen atmosphere, it is hard to prove the failure did not occur after the incident. Sensors decrease their voltage output during aging, and even if it is not proof of a faulty sensor, looking at the calibration voltage logged on the rebreather computer can give an indication of sensor failure, especially if the sensors are outside the specified calibration range.

Loggers

Given the difficulty of establishing the state of the oxygen sensors during an incident by post-incident testing, it is important to be able to read the sensor signals as they were logged during an incident, as is now possible with many rebreathers. This is a great help for investigating instances of hypoxia and oxygen toxicity, neither of which leave any trace that can be found during equipment investigation or by the medical examiner.

With loggers and downloads, the possibility for investigating such incidents is clear, but this must be done by someone highly familiar with the system (e.g., the manufacturer) to make sure that correct procedures are used and all information available is downloaded without loss. In Sweden, such downloads are done by the investigators under investigation confidentiality, usually by doing the download to the investigator's computer. When analyzing the logs, one must keep in mind that they record the sensor output signals and not necessarily the true value. Thus, it is necessary to check the sensor calibrations and consider the potential problems of each sensor type.

RESULTS

Accident statistics

Over the last 10 years in Scandinavia, 10 rebreather incidents have been investigated involving 12 divers. Of these, five have been lethal accidents, resulting in 0.5 fatalities per year with rebreathers as compared to the total number of nine fatal open-circuit diving accidents per year. In a 10-year perspective, rebreather fatalities are about 6 percent of the total. As rebreather fatalities make up about the same share of total fatalities for both the five- and three-year perspectives, there does not seem to have been a change over recent time.

To make the data more comparable to previous studies, we used the root-cause analysis and the format proposed by Vann, Pollock and Denoble (Vann et.al., 2007).

Trigger. Equipment problems occurred in seven of 12 cases. Buoyancy issues triggered one, and four were triggered by unknown causes. Examples of equipment problems were system in surface mode when diving, diver changed gas flow of semiclosed rebreather without checking resulting flow, and diver did not flush loop with oxygen prior to oxygen diving. A lost mouthpiece was the trigger related to the buoyancy issues.

Disabling agents. Eight cases involved inappropriate gas, two involved negative buoyancy problems related to loss of the mouthpiece, and the causes were unknown in two cases. Of the eight cases with inappropriate gas, six were hypoxia with loss of consciousness in three cases, one was oxygen low enough to result in decompression sickness (DCS) but not hypoxia, and one was oxygen toxicity in connection with hypercapnia.

Disabling injury. Nine were inappropriate gas, two were loss of consciousness, one was DCS.

Cause of death. Drowning.

These numbers are quite similar to the "rebreather fatality investigation" of Vann et al. (2007) with the exception that insufficient gas category as trigger and disabling agent does not appear in our cohort. Insufficient gas did not seem to be responsible for our unknown cases since there were no reports of low gas pressure in the diluent gas cylinders. On the other hand, there were too few accidents to state that insufficient gas does not occur.

Table 1. Compilation of Scandinavian rebreather incidents, 2001-2011.

Trigger	Fatal	Non-Fatal
Unknown	3	1
Negative buoyancy due to lost mouthpiece	x	1
HMI/procedural/equipment problems	2	5
Surface mode	2	1
— Unchecked change in semiclosed flow	x	2
— No O_2 purge of 100% O_2 unit	x	1
— Faulty PO_2 calculation leading to too fast ascent	x	1
Disabling Agent		
Inappropriate gas	3	5
— Hypoxia	2	4
— DCS due to low PO_2	x	1
— O_2 toxicity due to hypercapnia	1	x
Negative buoyancy due to lost mouthpiece	x	2
Unknown	2	x
Disabling Injury		
Inappropriate gas	5	4
Loss of consciousness	x	2
DCS	x	1

Cause of Death	Fatal	Non-Fatal
Drowning	5	—
Additional Findings		
Solo diving	4	1
Expedition diving	1	1
Maximum depth > 3 msw	x	4
Maximum depth 3-35 msw	3	3
Maximum depth > 35 msw	2	0
Semiclosed	1	5
Electronic PO_2 control	4	1
100% O_2	x	1
Under instruction	x	4
Instructors while teaching	1	1
Unit in surface mode on entering the water	2	1
Not operational upon water entry	1	x
No O_2 purge on 100% O_2 unit	x	1
Lost mouthpiece leading to lost buoyancy	x	2
Semiclosed unit gas flow was wrong	x	2
Deeper than MOD of diluent gas	1	x
Erroneous oxygen fraction calculation	x	1
No oxygen sensor	1	6

Of the five fatalities, four were solo dives. Of the twelve cases, two divers were participating in expeditions, 10 were diving shallower than 115 ft (35 m), six used semiclosed systems, five used electronically controlled systems, and one used a 100 percent oxygen rebreather. Four divers were in training, and two were instructors involved in teaching.

Four incidents involved units in surface mode or where the divers jumped into the water with their units not operational or in one case not having been flushed with oxygen on an oxygen rebreather. In two cases the mouthpiece was lost, resulting in negative buoyancy. Two cases involved a wrongly adjusted supply gas flow in semiclosed units, one case involved diving deeper than the maximum operational depth of the gas, and one case involved erroneous estimation of the inspired oxygen fraction.

DISCUSSION

There was only one case that could be attributed to hypercapnia. This was surprising given the vast number of anecdotal hypercapnia reports and because several failure points might cause hypercapnia, including check valve malfunction, various scrubber problems, work-of-breathing problems, or diver carbon-dioxide retaining behavior. Even though there was no evidence suggesting scrubber or flapper valve problems, one of the lost-mouthpiece incidents and some of the unknown accidents may have been triggered by hypercapnia.

Our statistics indicate there has been a shift in technology from semiclosed units toward fully closed units. This probably reflects the development of the market toward more electronically controlled rebreathers. Nevertheless, four out of six accidents with mechanical/semiclosed rebreathers could have been avoided had the divers known what they were breathing i.e. used an oxygen sensor in the loop. The other two cases were negative-buoyancy issues resulting from a lost mouthpiece. How to handle a lost mouthpiece must be a core skill in rebreather training.

The accidents caused by inappropriate gas were all due to procedural errors. The most frequent error was not turning on the unit correctly before entering water or making similar mistakes. Only two cases were not due to hypoxia: one from erroneous calculation of the oxygen fraction and the other from oxygen toxicity due to diving deeper than the maximum operational depth.

No accident could be related to equipment failure, and all could have been avoided by correct handling and/or operational procedures. In agreement with Vann et al. (2007), procedural/human-machine interface problems were overrepresented in rebreather diving as compared to open-circuit diving.

Thoroughness of investigations

Given the limited funding any police force has for "everyday" investigations, it is necessary to find a cost-efficient method to investigate rebreather accidents. When an accident occurs, we suggest that a review of the logs and the most probable failure issues should be carried out to select atypical cases for further investigation with the intent of better understanding of the inherent risks.

The first Swedish SHK investigation noted that the diver should have used a buddy line, which probably seemed sensible at the time, but today other methods have been developed for penetrating wrecks. No matter how thorough the investigation is, the reigning paradigm will almost always shine through. The best path to safety is by the cooperative efforts of the community, including agencies, scientists, manufacturers, training organizations and, not the least, users through discussions, publications, conferences and Internet forums that can change and evolve the safety paradigms. For this to happen, the involved parties need correct information, and that would imply the need for publication of incident investigations and fatality reports such as discussed in a recent letter (Vann, 2012). Publication of these reports would likely reveal that equipment failure is rare, and painfully simple user errors are the most common causes of these tragic events.

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HMS Hermes, *Sri Lanka. Photo by Andrew Fock.*

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DIVING ACCIDENT INVESTIGATIONS IN THE U.S. NAVY

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INTRODUCTION

The Navy Experimental Diving Unit (NEDU) conducts testing and evaluation for the U.S. military of divers' breathing equipment throughout its entire life-cycle. As part of this mission, NEDU conducts investigations on this equipment when it is involved in a diving accident. Although focused primarily on equipment used by the military, NEDU routinely conducts investigations involving divers from federal, state and regional agencies and occasionally sport-diving accidents. Open- and closed-circuit equipment as well as surface-supplied helmets involved in both fatal and non-fatal diving accidents are investigated to determine the probable causes. Any ancillary diving equipment, such as buoyancy compensators, that may have contributed to an accident are also investigated.

NEDU does not perform diving accident investigations for any organization or persons with a litigious purpose or financial interest in the outcome. Investigations involving military personnel typically include analysis of not only the equipment used during the accident but also the elements of training, operational constructs and maintenance schedules (Figure 1).

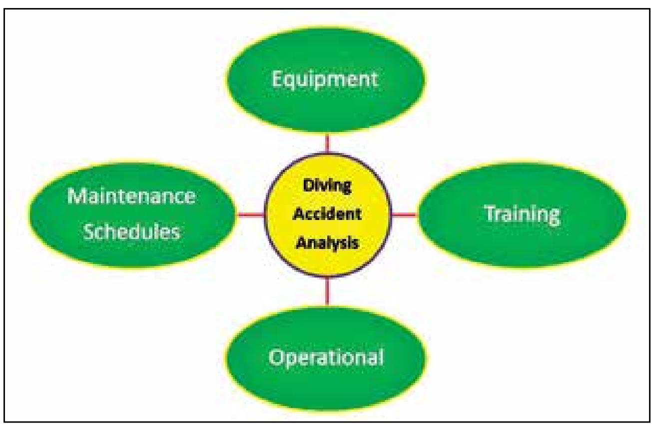

Figure 1. Components of an NEDU diving-accident investigation.

METHODS

All diving accident investigations start with establishing a continuous, unbroken chain of custody. The initial custodians are instructed by NEDU how to properly secure the equipment and package it for shipment to NEDU facilities while maintaining the configuration of the equipment as closely as possible to how it was used during the accident. Accident field reports and equipment maintenance logs are sequestered and sent to NEDU to aid in the testing and evaluation of the equipment. In the case of a rebreather, the remaining contents of the carbon-dioxide (CO_2) absorbent container from which the canister was filled may also be sequestered for analysis.

Upon receipt of the equipment at NEDU, an initial inventory and inspection is conducted. Photographs are taken to complement the inventory and to archive the condition of the equipment as received. All breathable gas sources that are part of the equipment are sampled and sent to an independent gas-analysis laboratory for determination of gas constituents and possible contaminants. Often the output of the compressors used to fill cylinders or provide surface-supplied gas is also sampled for analysis. During the inspection and testing of the equipment, the investigators look for details that may indicate equipment failure, improper assembly, inadequate maintenance, spent consumables or operational issues that may have contributed to the accident. Therefore, it is of the utmost importance that any dive profiles, dive logs, gas-pressure levels, programmed electronic setpoints, gas cylinder valve settings, sensor calibrations, adjustments or positions of various components of the equipment be recorded or downloaded in their as-received states and positions prior to further analysis or testing.

After the equipment has been inventoried and all as-received equipment parameters have been recorded, functional testing is initiated. For all types of breathing equipment, this includes a resistive effort determination using a mechanical breathing simulator. This is performed while the equipment is submerged in water in a hyperbaric chamber at the surface and often at a chamber pressure equivalent to the maximum depth of the accident dive. When an environmental condition, such as very cold water, is considered a possible factor in the accident, the equipment is tested in a similar environment. Accidents involving a rebreather typically include challenging the CO_2 absorbent in the canister in the as-received state by injecting a known volume of CO_2 into the breathing loop per unit time while the equipment is breathed using the breathing simulator and measuring the ability of the absorbent to effectively remove CO_2. (This test is omitted in the event the canister flooded during the accident.)

Many rebreathers utilize galvanic oxygen sensors for informational purposes or oxygen addition control. In accident investigations involving these rebreathers, the sensors are removed from the equipment and separately characterized for linearity and sufficient current generation (i.e., absence of current-limitation). When an electronic closed-circuit rebreather (eCCR) is investigated and, provided its oxygen sensors were adequately performing (as determined during the characterization tests), the sensors are reinstalled and the eCCR is tested to determine its ability to electronically control the partial pressure of oxygen in the breathing loop to preset values embedded in the electronics of the equipment.

After all testing, evaluation and analyses have been completed, the causes of the accident are hypothesized as supported by evidence. Possible causes may include equipment failure, inadequate maintenance, human error (on the part of the victim, support personnel or both), a medical condition (not investigated by NEDU), or even environmental conditions. For many accidents the investigator can only surmise as to which factors may have contributed based on the available evidence, in what order and to what degree.

Unlike most forensic investigators, the NEDU diving-accident investigator cannot return to the scene of the accident to collect additional evidence. Therefore, determination of the factual causes of an accident may not be possible from the evidence, at which point a presumptive causal inference is avoided. Many times the investigator may at best only be able to exclude possible factors from the accident causation.

RESULTS

NEDU has maintained records of accident investigations performed since 1978. A summary of these accidents appears in Figure 2; 53 were non-fatal, and 112 resulted in fatalities. Of these, 56 percent were using open-circuit equipment exclusively, 35 percent closed-circuit, and 9 percent surface-supplied helmets. (Some divers involved in accidents were equipped with either a closed-circuit rebreather or a surface-supplied helmet, had open-circuit bailout equipment or an emergency gas source [EGS] aside from the primary gas source during the dive, although it may have contributed to the cause of the accident.)

CAUSES

The factors to which the causes of the accidents were attributed were categorized as human, maintenance, equipment, and inconclusive. Figure 3 is a relational diagram of these categories for the 139 investigations (mostly open-circuit) with sufficient data for review. In all but one case human error contributed as a probable cause, but in 75 (45 percent) the evidence was not conclusive.

CONCLUSION

Along with advancing equipment technologies and ever more challenging dive profiles, human fallibility will always be with us. As divers, we will always do our part to reduce the incidence of diving accidents while recognizing they will never be nonexistent. As accident investigators, we must be prepared to extract as much information as possible from these accidents to help advance diver training and awareness and aid in the conception and development of future diving equipment and how it interacts with divers to make our underwater world safer.

PUBLIC DISCUSSION

PAUL HAYNES: We have accident investigators from three different nations here. We have seen Divers Alert Network (DAN) data where the cause of death in most cases, 95 percent, was drowning. We have seen Oskar's presentation, which backs that up. My question is, having investigated many rebreather fatalities, do you feel a mouthpiece-retaining strap might have saved a number of individuals?

OSKAR FRÅNBERG: I have not had enough experience with

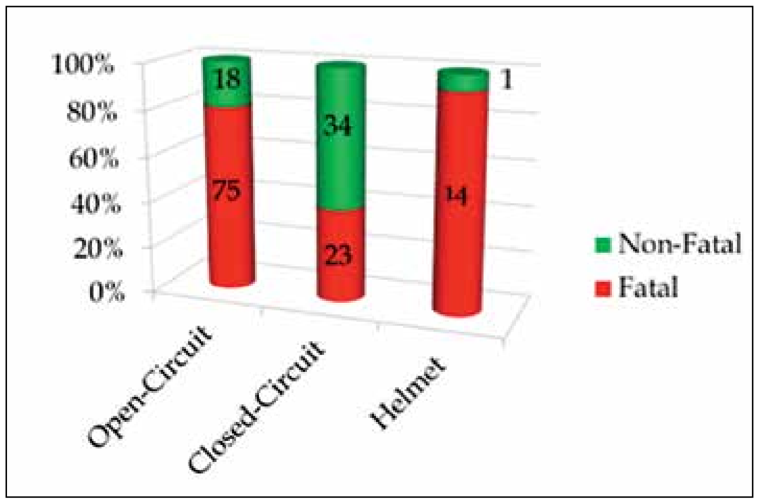

Figure 2. NEDU accident investigation count.

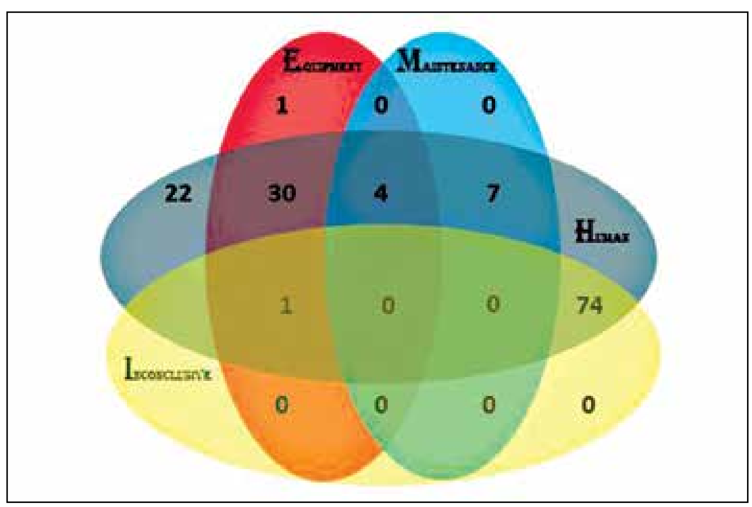

Figure 3. Relational diagram of causal categories in NEDU-investigated diving accidents.

the strap to have an opinion, but Swedish Navy diving is largely full-face mask. If you are going to use a full-face mask with a rebreather, you should have a bailout valve as well.

GAVIN ANTHONY: I think we have seen over the last couple of days that the postmortem cause of death is drowning in most cases. To drown, your mouth has to be open and water has to go in. If you have fallen unconscious, your mouthpiece has come out, you are hypoxic, water will go in your open mouth, and you will drown. That is a preventable outcome. If you can protect your airway, you will not drown, even though you may die of hypoxia or some other cause. The European standard requires that rebreathers have a system to retain the mouthpiece in the mouth or the face mask on the face to prevent drowning. I believe you should have at least a mouthpiece-retaining strap and preferably a full-face mask.

HAYNES: We should reconsider this as training organizations and manufacturers because we now have hard data. I think a mouthpiece-retaining strap would help prevent drowning as a cause of death. It might be enough time for your buddy to see you are in trouble. Someone described an incident where a diver became unconscious because of an allergy, lost his mouthpiece, and drowned. He would have survived that incident on land. We, as a community, need to change the culture. Thirty years ago there was public resistance to seatbelts, and the car manufacturers did not want them. The day seatbelts were enforced, driving fatalities dropped significantly.

UNIDENTIFIED SPEAKER: About six weeks ago, I dived with a mouthpiece strap on my rebreather. Now I probably would not dive without it. It is an idea that is worth pushing.

LEON SCAMMERHORN: The mouthpiece-retaining strap keeps the dive-surface valve (DSV) in your mouth, but it is not good enough. When I was a young serviceman diving a Draeger Lar V, we used a head strap to help prevent jaw fatigue. If you pass out and flip over on your back, it will prevent the breathing hoses from coming out of your mouth, but when you relax the jaw, water will still go in. A full-face mask is better because it decreases the odds of flooding the loop and drowning the diver. Keeping the loop dry is also beneficial because a rescuer does not have to keep the DSV in the diver's mouth and can focus on opening the bailout valve or flushing the breathing loop with diluent in case the gas is bad. This is easier with both arms available. A full-face mask is a good way to keep the loop dry.

RICHARD HARRIS: I agree with Leon that the mouthpiece-retaining strap reduces jaw fatigue but does not decrease the risk of water entering the airway. The RF2 proceedings also recommended using full-face masks. We used three or four commonly available full-face masks during cave diving in very cold water for thermal protection and to prevent drowning in case of an oxygen seizure, but we discarded them as they introduced other hazards. We were not formally trained in their use and perhaps could have done better; for the average diver, a full-face mask introduces complexities and hazards that may be worse than the problem we are trying to solve. It's not a simple answer and needs careful consideration.

RICHARD VANN: Unfortunately, drowning is relatively uninformative. You could drown as a result of hypoxia. You could drown if you run out of gas. We have to look further back in the chain of events that leads to the final cause of death. Frequently, a coroner records a death as drowning because the diver was found in the water. This has to go back to the cause of the event. To find this cause, first responders must be trained in diving-accident investigation, and instructors and dive operators need to know how to secure the scene in the event of an accident. This problem has not been addressed at RF3 as much as I hoped. Without good accident investigation, we will continue to be in the dark.

FRÅNBERG: I completely agree that one has to look down the chain of events. That is why I mentioned that the police do not want to investigate a death if drowning is the cause. But Paul also has a good point. If we can protect the airway, the likelihood of recovery is better.

BILL KISS: My impression from your data and data presented over the past two days indicates that equipment is an unlikely cause of rebreather deaths. If the technology is fairly safe, human error may be the most likely cause. What do you believe is the role of training in reducing human error?

VINCE FERRIS: I can only speak for the military, where there is a requirement for retraining or recertification that is missing in the civilian sector. As a diver, you periodically need to prove you can still do it. Look at the aviation community. Dr. Clarke flies a lot, and I have other friends who fly. Periodically, they have to prove they can still do it. That might be something to look into.

UNIDENTIFIED SPEAKER: In the Galapagos Islands we dive rebreathers from liveaboards that can be 120 miles (200 km) away from the central islands, which are 600 miles (1,000 km) away from mainland South America. We have not had an accident yet, but in case we do, what procedures would you recommend when there are no available medical or test facilities? We understand the equipment is usually not a causative factor, but it will certainly be questioned regarding liability.

FERRIS: I suggest you secure the equipment as best you can without making modifications and get law enforcement involved as soon as possible.

UNIDENTIFIED SPEAKER: The equipment would probably need to be transported by air, which means shutting off and removing the cylinders. You are altering the unit when you do that. What might be a reasonable procedure?

FERRIS: Establish a chain of custody for the equipment to identify who has handled it and what was done. Contact local law enforcement or coast guard, and let them decide how it should be stowed and shipped.

ANTHONY: The UK military has to face this situation because we deploy people all over the world, although our investigation center is in the UK. You need to put your procedures in place before you go so you know what to do. First, prepare a clear checklist of what to do and what not to do, particularly for rebreathers. Everyone at the dive site must be familiar with the checklist. Second, discuss the procedures with local authorities, and make transportation arrangements and arrangements with an appropriate test facility in advance. Air transport is particularly difficult because people usually do not want to fly a rebreather with pure oxygen cylinders and caustic material. The UK military will do so. I suggest these arrangements might be addressed at a more global level.

MARK CANEY: Vince, I presume from your talk, the majority of your incidents were military divers?

FERRIS: Not necessarily. There were a few civilian investigations, but we do all military investigations, and I did not break them down because I did not want anyone to think there were more military than civilian incidents.

CANEY: Presumably, a reasonable proportion of these divers were military. And speaker after speaker has described the human-machine interface and the human as the weak link in the system. We have reinforced things such as checklists in the Professional Association of Diving Instructors (PADI) rebreather training program to reduce possible human error, but the key point is the human seems to be the problem in a large segment of incidents. Although we can expect humans to perform adequately most of the time, they are going to have the occasional bad day. The purpose of an event like this is not only to take stock of where we are now but to lay foundations as to where we would like to go in the future. Would you agree it would be beneficial for the machine to reduce diver errors in the future?

FERRIS: I am going to answer as a rebreather diver, not as an accident investigator. I like to have as much control as possible. I like to know that I can flush with diluent, add more oxygen, or come off the loop. I like that better than having a computer tell me what to do. I would rather use my head as the computer. The obvious drawback is that if my head is not functioning well, maybe the computer should make some of those decisions.

FRÅNBERG: It is hard to give a definitive answer. Reducing the risk of problems is a good thing, but there might be many ways to do it.

MARTIN PARKER: Buddy separation or diving alone was prominent in many fatalities that ended in drowning. Mouthpiece-retaining straps and improved rebreather technology might reduce drowning and so would diving with a buddy. We should encouraging buddy diving.

Figure 4. The author, hoping not to become the subject of an NEDU rebreather accident investigation. Photo by Dr. William Huth , University of West Florida, Marketing and Economics Department.

FIVE GOLDEN RULES: SHIFTING THE CULTURE OF REBREATHER DIVING TO REDUCE ACCIDENTS

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ABSTRACT

Closed-circuit rebreathers (CCRs) have been connected to approximately 20 deaths per year in the sport-diving community. Significant evidence supports that these fatalities are often tied to failures of the human-machine interface (HMI) as well as risky choices and behaviors. This presentation aims to suggest a cultural shift in CCR diving that minimizes and prevents future deaths. According to recent statistics, approximately 20 of our rebreather colleagues are dying on their units each year. I propose a resolution, a cultural shift in CCR diving that might lower this number significantly. This shift consists of adopting five basic rules in your personal diving as well as insistence that your buddies follow the same responsible guidelines. The rules fall into the following categories: training/currency, checklists, prebreathe, decision to dive, and aborting dives. Whether you are new to rebreathers or an experienced CCR diver who feels very comfortable with them, these rules could save your life.

Keywords: abort, checklist, complacency, prebreathe, predive check

Figure 1. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

Figure 2. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

RULE 1: RECOGNIZE AND PREVENT COMPLACENCY IN YOURSELF AND OTHERS AROUND YOU.

Accidents are frequently labelled as "pilot error," so it behooves us to examine the nature of pilot error. Technical diving, and specifically rebreather diving, is a continual learning process. If we closely examine how we learn, we can better prepare for the pitfalls associated with each stage of the learning process.

For example, an internationally recognized climber threads the rope through her harness on an easy climb. She is temporarily distracted by someone with a question, and while answering, she stops to tie her shoes. She makes her climb, and when she leans back to rappel, she falls 72 ft (22 m), narrowly escaping her death when cushioned by tree branches. In her case more training would not have helped. Experience actually contributed to her accident. She tied off when she was supposed to routinely tie off — but rather than her harness, it was her shoes.

I am going to explore how we learn and how we can continue to stay sharp in everything we do. There are five easy steps to remember, and if you understand the path to learning and experience you can increase your skill level in anything to which you aspire and become safer in the process.

Gordon Training International is popularly considered to be the originator of the Conscious Competence model, which describes the steps involved in the process of learning any new skill (Burch, 2012). This model is particularly applicable to rebreather diving.

The model describes the first stage of learning as "Unconsciously Unskilled." This stage accurately characterizes a rebreather diver on his or her first day of class; he is unaware of the proper function of the unit and incapable of determining the risk. He simply does not know what can kill him or how it might happen.

Stage two, and each stage thereafter, illustrates a sensation of awakening, when the person feels "like a light bulb went off." As the diver takes this step forward, he enters the realm of "Consciously Unskilled." At this point, the diver is beginning to understand the function of his unit and is able to assess risks but still needs close supervision.

Figure 3. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

Next, the learner reaches the point of "Consciously Skilled." This may be the point when he completes his initial rebreather training. At this level, the diver has mastered basic controls, has a good assessment of risk and is able to complete "self- or buddy-rescue." This may indeed be the point where he is the safest rebreather diver he can ever be. He still has a healthy fear that the unit may fail him and is consciously driving the rebreather with great care.

The final stage of learning occurs when the diver reaches the "Unconsciously Skilled" level. This is akin to someone who has been driving a car for a long time. He makes his daily commute and barely recalls the route he took or the things he saw along the way. When this occurs in rebreather diving, it is often the point when complacency kicks in.

I have often thought that new rebreather divers with roughly 50-100 hours after their initial training may be at the greatest risk in their diving careers, especially if nothing has scared them along the way. The human brain is exquisitely tuned to

Figure 4. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

detect novelty, but when everything becomes routine we tend to stop paying attention. Yet, according to Dr. Jeffrey Schwartz at the UCLA School of Medicine, humans can literally alter the anatomy of the brain by the demands required of it (Aalito, 2012). He noted that the hippocampus of cab drivers grew larger as they learned the layout of a new city. The hippocampus is responsible for map-making, and he noticed profound neural changes that occurred within a few days.

When a rebreather diver experiences a serious gear malfunction, it often frightens the diver back to the previous level of learning, when he becomes a conscious driver of his unit again. A long absence from diving will also result in the diver stepping backward in the model until he catches up with his skills and practice.

The climber who experienced the fall was attempting to use a behavioral script to prepare her harness. Using her memory, she conducted a series of steps she had done repeatedly without incident. At the moment when her mental model indicated that she should tie her harness, she was distracted and instead tied her shoe. This action likely satisfied her behavioral script, and she moved on to the next phase of her climb. Her mental checklist had become routine.

Figure 5. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

To avoid the pitfalls of complacency, proper procedures and a commitment to predive checklists and prebreathe sequences are critical. A diver who carefully reviews his personal preparedness as well as his equipment readiness will be better poised to deal with the issues he may encounter ahead.

RULE 2: ALWAYS USE A WRITTEN OR ELECTRONIC CHECKLIST TO PREPARE YOUR REBREATHER.

Many fatalities could likely have been prevented by using a paper or onscreen checklist. Distractions and lapses in memory are human factors that we need to account for in all diving activities. It is incumbent on instructors, mentors and prominent divers to change the culture of rebreather diving to something equivalent to flight training. Checklists have to be viewed as “cool” to be popular. When failing to use a checklist is frowned upon at the grassroots level, then they will be more widely utilized. Role models and thought leaders within our sport need to be conspicuous in using checklists and insistent that their diving partners do the same.

Figure 6. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

RULE 3: ALWAYS CONDUCT A FIVE-MINUTE PREBREATHE IN A SAFE, COMFORTABLE PLACE WITH YOUR NOSE BLOCKED.

A five-minute prebreathe should become the norm throughout our industry. Students and diving partners need to be encouraged to conduct this activity in a seated and safe location so they can observe their handsets, listen for their solenoid and evaluate their physical condition prior to reaching a place of danger where they could fall and injure themselves or drown. Initial prebreathe sequences should never be conducted while walking to a site entry, putting on fins or floating in the water.

RULE 4: DO NOT DIVE IF YOUR REBREATHER HAS NOT COMPLETELY PASSED ALL PREDIVE CHECKS AND TESTS.

A significant number of accidents and fatalities are attributed to high-risk behaviors such as beginning a dive with a known

Figure 7. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

technical fault such as a single sensor failure. These faults may not be detected until a prebreathe is attempted, so if it is still critical to do the dive, then it is incumbent on the diver to have alternative equipment available to make the dive safely.

RULE 5: ABORT YOUR DIVE IN THE SAFEST-POSSIBLE MODE.

In the early history of rebreather training, we always encouraged divers to find a way to stay on the loop if possible. Culturally, this flawed practice may have led to incidents where divers felt it reflected poorly on them when they bailed to open-circuit. In most cases today, a properly equipped CCR diver has sufficient personal gas to execute an open-circuit bailout. If you have sufficient gas for abort, open-circuit is the safest option and definitely preferred when diving alone.

Whether the abort takes place on the boat deck or during a dive, the community needs to be encouraged to follow safe role-model behaviors. Refuse to dive with those who do not abide by essential safety measures. Refuse to dive with those who take unnecessary risks for themselves and their team.

Figure 8. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

Dr. Andrew Fock's research has revealed that most fatalities are attributed to diver choices and behaviors rather than any particular model or style of rebreather (Fock, 2013). Given that revelation, we have a unique opportunity to grow the market in a safer way by encouraging and applauding safe diving practices and focused attention to procedures.

Figure 9. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

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Figure 10. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

Figure 11. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

Figure 12. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

FAILURE IS NOT AN OPTION: THE IMPORTANCE OF USING A CCR CHECKLIST

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It is hard to believe that I am actually standing in front of people now talking about rebreathers, because back in 1996 I was quoted in the book *Shadow Divers*, in an interview in the back, saying that I would not dive a rebreather. The reason for that was that my dive partner at the time, John Chatterton, considered himself a bit of a test pilot and was using various experimental and homemade rebreathers. The outcomes were not always good, so I recognized that for me the technology had not yet arrived.

It would not be until working on the television program *Deep Sea Detectives* when I was a member of a four-man team — with John Chatterton, Evan Kovacs, and DJ Roller — and I was the only open-circuit cog in the machine. The other three were all diving Inspiration rebreathers, and over a period of roughly three years we dived in a variety of conditions, some quite remote. During that time there were absolutely no failures of the rebreathers. In addition, the advantages of diving a rebreather became evident to me, especially on some of the deeper dives. With that motivation to re-examine my position and the advent of Ambient Pressure Diving's Evolution rebreather, I became a convert. In time, I was so impressed with the new technology and all its advantages, I felt compelled to work up to becoming an instructor. I love the ability this technology gives me, but this ability comes with a cost.

As an instructor, I often draw parallels between flying and diving a rebreather. The reality is that both activities are dependent on machinery, and the outcome is almost totally in your hands. When you look at the Federal Aviation Administration (FAA) accident reports, there are many cases of pilots flying good aircraft into the ground. I find similarities in the closed-circuit world in recent years, where glib divers are flying good rebreathers into the ground.

Your life support is dependent on the rebreather being properly maintained, but rebreathers do not have the regulatory control that is in place for aircraft. Planes cannot fly unless they have at least minimum regular maintenance and inspections. The final preflight inspection is done by the person who will fly the aircraft, and this is guided by specific checklists, as are the other phases of flight. The diver strapping on a rebreather is in a very similar position.

Human beings will make mistakes and have memory lapses. I drive this point home not only to the people who are interested in looking at rebreathers but more important to my peers with long experience. Complacency settles in because the technology does work. So when we are assembling our specific units, we need to meticulously follow checklists so we do not miss the one item that could make for a bad day. Many pilots have support teams, including ground crew and air traffic controllers. But they also personally accept the responsibility of preflighting the aircraft.

Figure 1. The checklist is the primary defense against something going wrong and being prepared for it if it does. Photo courtesy Richie Kohler.

We need to be at least as diligent in checking out our rebreathers before we get in the water because we do not have the same maintenance and inspection requirements, ground crew, or water traffic control. You are the pilot and ground crew taking your life quite literally into your own hands.

The closed-circuit rebreather (CCR) checklist is important because there are lots of little parts that must be assembled in a very specific fashion. The predive checks should ensure that the unit is on and that everything is correctly assembled. It should guide you to predive (prebreathe) the unit while sitting on the boat to make sure everything is up and running. The checklist is your primary defense against something going wrong and, if something does, being prepared for it.

One of the things I teach my students is that even if you always follow the checklists you cannot guarantee that the unit will not fail. Any machine or system can break. But by following your checklist you have gone a long way to avoiding problems.

Equally important, you have prepared your options for bailout or self-rescue if failure does occur.

Getting back to the parallels between diving and flying, the first time I sat in the cockpit of a helicopter it occurred to me that there were many similarities to rebreather diving. As a helicopter pilot, I have the cyclic in one hand, the collective in the other, and both feet on the pedals. A lot of input is required for controlled flight in three-dimensional space. Rebreathers have a much higher level of complexity in comparison with open-circuit systems. A very smart person once said that the most dangerous thing you will ever do is manipulate your own breathing medium, and that is what you are doing on a rebreather. It is your obligation to make sure that you are constantly on the stick, because as in flying a helicopter there is no autopilot. You need to constantly monitor the rig. Let it get away from you, and it will kill you. A glaring difference is that the aviation community has a stronger emphasis on building a culture of safe preparation practices that I do not see in the rebreather community. My flight instructor made it crystal clear that any item that failed on the checklist would constitute a no-go flight. We need to achieve that same level of appreciation of the CCR checklist's importance; you fail anything on the checklist, and the dive is aborted.

Regardless of what rebreather you have, there is some common ground and a very specific order to follow on the checklist. You need to analyze and correctly label gases so that there is no mistake between your oxygen and diluent. You need to confirm that your scrubber material is adequate for the planned dive. You need to assemble your unit in a specific order. I personally like to assemble my unit the day before a dive. Doing it on the day of the dive gives you fewer options in case you have a problem. Give yourself plenty of time during assembly, follow your checklist, and check everything. Accept zero failure. There is nothing down there that is so important that you need to risk your life because of a small component that was not 100 percent.

After powering up the assembled unit you need to confirm that the cells are working, that the electronics are within parameters, and that everything is ready for diving. Only after full satisfaction of the checklist are you ready to do the predive sequence and test the unit on the surface. You should prebreathe a rig for a minimum of five minutes. Make sure that your scrubber material and cells are reacting, the gases are flowing, and appropriate levels are being held. Your primary defense is correctly completing the right checklist.

Prior to entering the water you physically check again that all gases and electronics are on. Check gauge response and computers, looking at them before and after you put that loop in your mouth. Confirm your setpoints and decompression information, and only then are you ready to dive.

Great rules that I cannot take credit for are that we should never put a rebreather on our backs unless it is fully turned on, preflighted and operational, and that we should never turn off a rebreather until we have taken it off our body and it is on the bench. Many divers have jumped into the water with a rebreather that had been operational earlier but is currently shut off. Distractions can make it easy to forget to turn it back on in time. The simple rules of not ever donning the unit unless it is on and not turning it off until it is off your body can make a huge difference in safety.

Figure 2. You must physically confirm ALL gasses are on BEFORE entering the water. Photo courtesy Richie Kohler.

Checklists are always going to be specific to a given unit. Many of us like to customize our rides, including rebreathers. There are "aftermarket" parts that, once added, will demand checklist modification. Strapping on a new piece of equipment or modified equipment requires appropriate training and incorporation into checklists before diving.

Failure to do everything right makes failure inevitable, it is simply a matter of when. This is no different from a pilot reading a book and not watching as he flies into an antenna. You have to be on the ball. You have to be willing to commit this level of attention and responsibility if you want the added benefit of diving a rebreather.

The human element is the most fallible. We prepare and train for equipment failure. We have a great advantage over pilots who cannot jump into another airplane midflight. We can carry bailout systems and use them. But our checklist is our primary defense to not ever having to get there.

This symposium will consider accidents that have occurred while diving rebreathers. You may hear analytical and dispassionate presentations, but we must remember more. I have lost really close friends diving on rebreathers in the last few years. Each of them planned to have a good dive, but in the end they did not come home. Some died very shallow, some died very deep.

I like to keep their faces with me. They were not fools, but they made foolish mistakes. Each experienced one or more events that can be described as a failure:

- incomplete use of a checklist
- failure to turn on oxygen
- jumping back in the water and not realizing the oxygen was off
- failure to properly analyze and label gases
- failure to change scrubber
- failure to monitor PO_2

These divers flew working aircraft directly into the ground.

Other cases included failure to be appropriately trained and qualified. Although not a traditional checklist item, I mention it because this can happen with experienced but complacent rebreather divers who wrongly think they can master something new without proper training. Or it can happen to entry-level individuals who choose to go a little further than they are ready, whether it is diving too deep, too long, or with gases for which they are not trained.

Failure to have proper bailout is another common problem. There are different schools of thought on how bailout should be prepared, for example, whether you should have the valve open or closed as in open-circuit technical diving, where you would keep your gas charged but off. I prefer instant availability for either a bailout valve (BOV) or offboard gas. Failure to have proper and working bailout, including bailout with no regulator on the tank, has directly played a tragic part in actual accidents.

Figure 3. Always know your PPO_2 — check your handsets every one to three minutes. Photo courtesy Richie Kohler.

The most important thing I want to impart to you is that many of these divers were smart. But they made mistakes. We all should not fail to learn from their mistakes. We need to approach rebreather diving with reverence and remain humble to it. This is the best tool for me to use, but it comes with a price. I do not want to pay the ultimate price. I am willing to take time to make sure that my unit is correctly assembled and my procedures are sharp. Failure is not an option.

Figure 4. CCR bailout O_2 options. Photo courtesy Richie Kohler.

Prebreathing your CCR before donning is paramount to confirm the unit is assembled and functioning correctly prior to entering the water. Photo courtesy Richie Kohler.

Optima CCR. Photo courtesy Richie Kohler.

CCR diver entering the water. Photo courtesy Richie Kohler.

CCR wreck diving. Photo courtesy Howard Ehrenburg.

Full-face mask. Photo courtesy Richie Kohler.

OPERATIONS AND TRAINING

Editors' note: The following text was excerpted from a transcript of the meeting provided by a court reporter. Editorial changes were made to correct grammar and remove extraneous comments. Every effort was made throughout to retain the spirit and intent of the original discussion. The session was moderated by Jeffrey Bozanic.

NEAL POLLOCK: Welcome to the operations and training unit. Phil Short will start off this session as a primary organizer. He has had an interesting history. He started diving in 1990, became an instructor in 1991 and turned to technical diving in 1993. Since then he has focused on it professionally. He has logged more than 6,000 dives and gained a wealth of experience through the accumulation.

PHIL SHORT: The introduction to the whole operations panel will be given by Jeff Bozanic. He has been rebreather diving since 1988. He has extensive experience on many types and is well known in the community for his textbook *Mastering Rebreathers*. Wayne Quarberg will provide the operations survey. He is president and CEO of Multinational Diving Educators Association International. He designed the Frog Mach 1 rebreather and is a scuba- and commercial-diving instructor. We are then onto the use of rebreathers in institutions. Dave Conlin from the National Park Service (NPS) will present first. He holds two master's degrees and a doctorate in archeology. He was an archeologist for the U.S. Navy and chief of the National Park Service Submerged Resources Center. Doug Kesling from the National Oceanic and Atmospheric Administration (NOAA), University of North Carolina at Wilmington (UNCW) and University of Puerto Rico (UPR) will follow. He is manager of the advanced-diving program and Aquarius habitat senior technician. Rich Pyle of the Association for Marine Exploration and the Bishop Museum will close the group. He pioneered the use of rebreathers in what is known as the twilight zone. I will then be back on the stage to discuss technical versus recreational rebreathers, training concerns and differences between training recreational and technical divers and problems and solutions. Nancy Easterbrook will then talk about supervision. She is the owner of Divetech in Grand Cayman, a boat captain and instructor trainer with 20 years of experience in the industry. Jeff Bozanic will then talk about procedures, looking at checklists, predive protocols and procedures, solo diving, and whether divers are going too far too soon. Forrest Gauthier will then talk about science versus opinion. He has a Queens Award for technical excellence in the UK, holds more than 30 patents, and has been diving since 1971. Danny Graham will then talk about prebreathing. He began diving as a sea urchin harvester and started Nuvair in 1998. Jeff Bozanic will return to talk about cleaning, disinfecting and maintenance of rebreathers and conclude the panel.

JEFF BOZANIC: We are in a position where our corner of the industry, rebreathers, is beginning to mature. With that maturity will come growth beyond the early generation that primarily used rebreathers to extend the limits on what was possible with diving and diving exploration. We are not here to try to stifle that growth. In fact, quite the opposite. We are here to try to foster that growth and bring more people into what we are doing safely. We want to bring operational parameters to a new level of safety. We have all seen the accident statistics that are out there. We agree that we need to identify some of the things we need to do. Finally, we want to support a process where we all cooperate together to continue improving. That is our goal. Wayne Quarberg will talk about a survey to set the stage for where we are so we have a better feel for where we are going.

WAYNE QUARBERG: We have prepared a short survey for current closed-circuit rebreather (CCR) procedures. The goal is to see how divers are using CCRs in real life. We are asking for honesty on actual practices, not what we should be doing. Topics include checklists, scrubber, bailout, diving, training, user experience and cleaning. Participants will remain anonymous. We will also post this survey on the Internet so those not attending this conference can also participate.

BOZANIC: We are now going to consider how different types of institutions have operationally implemented rebreathers and some of the things they have done to increase the safety of the technology in their programs.

DAVE CONLIN: I will share what we in the NPS do; how we came to rebreathers, how we use rebreathers, how we as a federal institution incorporate this technology into our daily operations, and how we arrived at some of the decisions that we did. Some of the things I am going to say may be a little controversial. My intention is not to stir things up but to openly discuss what we do.

The NPS has the oldest non-military diving program in the U.S. federal government. The first park ranger certified to dive for the agency was certified in 1959. The NPS has a long history of operational innovation to achieve agency goals, including the use of flight, snowmobiles, and diving. We maintain a mission-oriented focus. The park service as an agency has not been slow to embrace new things to help us protect resources unimpaired for future generations and to provide recreational opportunities for people to enjoy. Our mandate stretches from Maine to Puerto Rico, Alaska to American Samoa, Guam and everywhere in between. NPS rangers dive in all sorts of conditions. They do search and rescue, maintenance, address natural and cultural resources and facilitate interpretation. We work in a range of environments on a variety of tasks that vary from park to park. Some park dive teams have only maintenance people. Some deal with only natural resources. The NPS has about 5 million acres of submerged land. We have approximately 5,100 miles (8160 km) of ocean shoreline in 26 states and territories. That is more coastline than the country of Brazil. We have about 200 NPS divers and 35 different teams throughout the system. My part of this is the Submerged Resources Center. We were established with the best acronym in government as the SCRU team. In 2000 we became the Submerged Resources Center (SRC) to encompass natural resource work as well. We are primarily underwater archeologists but also photographers and videographers. We are a core team that works with park dive teams, partners, and others. We form a center of expertise around which we build projects and programs throughout the national park system, but we also work worldwide as well. We are divers, scientists and park rangers.

Our introduction to rebreathers came as a result of a specific project (Bozanic, 2007). In 1948 a B29 Super Fortress out of what became China Lake crashed in Lake Mead during a top-secret, high-altitude research mission. The wreckage was discovered in 2000 by a local diver. He and his team dived on it for two years. In 2002 the Park Service started diving on it. We were called out to help map and understand the documented remains of this plane. It crashed in the Overton arm of Lake Mead. It is about 100 miles^2 (259 km^2) of lake. The depth when we first started diving on it was 185-190 ft (56-56 m). Due to the altitude we were calculating those dives as >200 ft (61 m). The plane pancaked into the lake, and three of its four engines were torn off. All five crewmen got out alive, fortunately, but it sat undiscovered for a long time. So the park had a need, and we were the people to come out and do the documentation.

Just so you know, too, as the lake level raises and drops, the depth at which the site is changes as well. It was colossal logistics of diving this plane on open-circuit that pushed us to closed-circuit. Fortunately, the park service gave the go ahead to use this technology even though it was a little bit experimental. We made the switch from open-circuit to closed-circuit in 2005. Jeff Bozanic had provided our mixed-gas open-circuit training, and since he was also teaching rebreathers, he agreed to help us use them operationally, allowing us to move on from there.

We chose the Ambient Pressure (AP) platform due to availability, capabilities, and the support network the company had at the time. We are not endorsing any particular units. I am just talking about what we chose. One thing I would emphasize for suppliers and the manufacturers is that your customer service and support are every bit as important as the quality of the equipment that you produce. We can have the greatest piece of equipment in the world, but if it breaks in the field and we cannot get someone to help us to keep the operation rolling, then it is no good to us.

We made a conscious decision that we were only going to use rebreathers for 18 months regardless of the dive depth or the profile. Yes, it was odd gearing up on our rebreathers and doing our predive checks to do a 15-ft (5-m) dive on the USS *Arizona* in Pearl Harbor, but having hours, muscle memory, a clear understanding of how the system works and what can go wrong, and knowing how to troubleshoot was really important. We know that some use rebreathers only for deep dives. Our feeling was why use your most complex piece of equipment only to execute your most dangerous dives. If I am going to screw something up, I want to screw it up at 10 ft (3 m), where I can stick my head out of the water, and not at 300 ft (91 m), where I do not have that option. We dived our rebreathers with air as a diluent for 80 hours of diving before we switched to mix. We used heliox with a PO_2 of not more than 1.0 atm at depth. In practice we used a 10/90 (oxygen/helium) mix. We wanted a lean diluent in case of a stuck solenoid. Going with that, we understood the problems of isobaric process, so we had a normoxic heliox as a bailout so we were not switching. This is something that we did that some others laughed at, but I believe it had some logic.

We cut tables on a 1.1 atm PO_2 setpoint, and we dived our units on a 1.4 atm and spun them up to a 1.6 atm at deco. We were asked why we did this with dive computers. It was a safety margin that we built in for multiple days of diving. As we have gotten more experienced, people are cringing over diving at 1.4 atm. We are not doing that anymore. Our feeling is that we are more concerned about the nitrogen side of things than the oxygen. So our computers were only for emergency bailout. As I said, we are concerned with the nitrogen side of the decompression equation, and we preferred longer deco times that came with heliox than having nitrogen. Our feeling is that for a very small bottle of diluent, if you do not have to have any nitrogen at all, why would you have any nitrogen at all? We were willing to accept a higher oxygen exposure for our dives. I am skeptical about the concept of oxygen toxicity units (OTUs). I personally felt that there was a lot of stuff that gets repeated in the dive community that is taken on faith and not really examined closely. So we were willing to ask the dumb questions of why that is. But if anyone wants to ask me about my intent to use heliox for a drysuit inflator source, I would be happy to tell you that story. That did not really work out so well.

We use tested and validated Buhlmann algorithms. We chose our decompression not because it got you out of the water faster, but because we felt like it was safer. We are willing to put some staff in full-face masks for filming or due to individual medical reasons. Then, in 2009, two of us went to the Sentinel platform because we felt like we needed more of an expedition unit for deeper diving. We appreciated Kevin Gurr's philosophy about not making a diving unit but making an underwater life-support system. We liked the CO_2 sensor, and we also liked the backmounted counterlung.

We currently have seven rebreather divers in the National Park Service, all on the SRC team. We have more teams looking at rebreathers in Florida and American Samoa and possibly Iowa. We use them mostly for filming and underwater archeology. We do not do a lot of really deep diving, at least not in 2011. The true strength and value of rebreathers for us is not depth but longer working times, primarily in the 70-100 ft (21-30 m) range. This allows us to take advantage of good weather, particularly on remote sites. When you are in Isle Royale at the top of Lake Superior or on the U-boats in North Carolina and the weather is good, you want to work all day long.

Practically, we believe that rebreathers are the best available technology to use for specific types of operations — deep, cold and overhead. We believe that the training requirements in diving complexity have increased but not inordinately. We believe that switching to rebreathers is an all-in or all-out decision. And it needs follow-through and commitment by the agency that you are working for. We have seen project logistics decrease, research time increase, and we feel that this is a much, much better use of our scientists' time than pumping tanks all hours of the day and night. We have seen the greatest benefit of rebreathers in the shallower range, and our time in the water has increased significantly. This is the take-home message. According to our diving safety officer's report on 2011 dives, we have seen a 38 percent increase in diver productivity after adopting rebreathers. So we have seen an extra 15 minutes on our average dive time. While that may not seem like a lot, it represents one extra day for every three days we are in the field, and that makes a difference.

BOZANIC: I would also like to state that there are parallels with what is happening on the recreational side of our industry now where we can expect to see rebreathers being used not for deep or technical exploration but also for day-to-day use at resorts and local diving. Now we hear from Doug Kesling and his experience.

DOUG KESLING: I am here representing the scientific-diving community. For background, I consider myself a novice rebreather diver. I have about 10 years of experience with rebreathers, including 150-plus dives and 150 hours of bottom time. I am currently a consultant with my company Aquatic Training Systems, based in Wilmington, NC. I am going to share the science component for some of the work we have been doing in the past few years in the American Academy of Underwater Sciences (AAUS). For about 20 years I was based

Figure 1. Clean shot, unfettered, easy to access gauges and buttons. Photo by Richie Kohler.

at the National Undersea Research Center at the University of North Carolina at Wilmington. It was a NOAA-funded program. We also operated the Aquarius reef-based platform. As with a lot of the things we do in scientific diving, we look at the benefits versus the risks. We have had a lot of success but also some failures. Martin Parker described a bit about the fatality that occurred in the Aquarius. It is a sobering point to think about your own personnel having a situation like that.

Unfortunately, funding ran out in October, and the National Undersea Research Center in Wilmington was shut down. I understand the Aquarius program will also be closing if it does not secure future funding shortly. From an operational standpoint, our activity is often driven by a need for technology. The Undersea Research Center had been that arm of NOAA. My involvement with the rebreather began in 2006 based on a NOAA need to do some work in deeper coral-reef environments. We were asked at our center to help the team utilize advanced tools. Over the course of the last six years or so we have conducted and supported 850 manned CCR dives. We reached 303 ft (92 m) and accumulated 900 hours of bottom time (with much longer total run times).

The University of Puerto Rico received second-phase funding from the National Center for Coastal Ocean Science and the Center for Sponsored Coastal Ocean Studies in 2006. The first phase of funding addressed coral-reef environments in 2002. And the next step in this process for marine science and conservatism of these reefs was to fund the project in 2006, which happened in Puerto Rico and subsequently 2007 out in Hawaii. We were asked to help spin up the team of faculty and graduate students to use ultimately advanced deep-diving technologies for this research into these deep reefs. The timing was good in that we would not have been able to do this on open-circuit.

Our goal was to develop this science team over two or three years to be able to access deep coral reefs. They start at about 100 ft (30 m) and go down to about 330 ft (101 m). We needed a safe, effective way to get down there, spend time, do observations, collect data, and get back. For us scientific diving is a tool, using open-circuit or rebreathers. We were looking at the continuity between the shallow reefs and deeper reefs, the after-effects of stress and human intervention, fishery resources, and things like that. The effort was collaborative. We had a very good agency in Puerto Rico. We got additional training, had service and manufacturing support. We received good support over the years from AP for the Inspiration. The other thing I want to highlight is that many who have gone through this training felt that some of the open-circuit technical-diving training they received prior to the CCR was very instrumental in working out issues of decompression and emergency procedures.

We were recently aboard the motor vessel Spree of Puerto Rico: 12 days, 59 person-dives on trimix, and 22 person-dives on air diluent. We accomplished a lot of work in the 12-day period. We felt that the extensive open-circuit mixed-gas training was good prior to the CCR use. We did a three-tier approach on the CCRs. Diving the CCRs on a regular basis is very important to develop and reinforce protocols and procedures. Predive checklists and gas analysis were emphasized along with standardization among the dive teams. We have an onsite dive supervisor, top-side support. Deck checks are completed prior to the water entry. Fully developed emergency assistance plan, sometimes including portable hyperbaric chambers, are maintained.

Some of the problems that we have seen program-wide with the research center have involved the use of checklists, carrying off-board bailout gases, buddymanship, monitoring on-board instruments and gas supply, the ability to plug in off-board gases, unnecessary distractions during CCR setup, not recognizing problems that would force bailout, decompression monitoring, backup computers, and incomplete compliance with the maintenance programs for both essential diving equipment and ancillary support equipment. Our solutions include reliable checklists, well-maintained buddymanship, frequent diving; maintenance, team approach for staging off-board bailout gases and practice, practice, practice.

BOZANIC: Continuing with an overview is Richard Pyle.

RICHARD PYLE: I am going to discuss a mixture of projects; a sampling of the places we have been over the last 25 years. The first few years, from 1988 to 1994, was with open-circuit trimix. We then switched to rebreathers for a bunch of reasons. We have spent the most time in tropical regions. Nigel Jones was teasing me this morning, saying that with the environments we dive surely our greatest risk is sunburn. To some extent that is true, but we have other sorts of logistical issues to address. Our motivation for deep diving is biological. I go after new species of fishes. We found more than 100 new species, a remarkable number.

Our challenges are the diversity of the circumstances we find. We often dive from, small, open boats but can be lucky enough to work from liveaboards or even luxury liveaboards where your hotel room and your dive platform are about 15 ft (5 m) apart. The latter can make things much easier. Know, though, that we have done 400-ft (122-m) dives from an outrigger canoe. This actually turned out to be one of the best diving platforms we have used because the outrigger made it fairly easy to get in and out of the water without much exertion. We have also conducted major operations where there is no electricity and the running water is a little brook near the compound.

One of the things I should point out is that it was our pattern of going through a lot of helium that led us to rebreathing in the first place. A theme common to Rebreather Forum 2.0 and now is the need for maintenance, maintenance, maintenance. We did a project with NOAA in the late 1990s to actually quantify this. We had a mixed-gas rebreather team and a mixed-gas open-circuit team. The closed-circuit was far, far better in terms of sufficiency in terms of gas usage and even better in terms of actual costs. In terms of gear configuration, most of these dives were done with a Cis-Lunar Mark V rebreather with on-board oxygen supply, off-board trimix supply, and a secondary bailout oxygen supply. We also generally stage different gas mixes at different depths. We have different techniques of getting access to that. More recently we switched over to using the prototypes of the new science tech unit. We find ourselves much more maneuverable with less equipment on our back.

Almost all our dives are in very remote locations, often days from the nearest recompression chamber. A lot of this has been published in the Undersea and Hyperbaric Medical Society (UHMS) proceedings a number of years ago. Where do we go from here? We have a NOAA-funded project in Hawaii, and last year we were able to put together a team with the University of Hawaii submersible. Each of those technologies has advantages and disadvantages. Working together we were able to get certain kinds of science done that could not have been done by either of the technologies alone. More recently we were able to do true tandem rebreather and submarine diving, which was great. The submarines were essentially our limousine. We get on the back of the submarine at the surface, and the submarine finds the site with sonar and takes us right on the spot. The submarine then becomes the ultimate dive buddy with all kinds of bailout mechanisms. This was a really successful approach that we are looking forward to fleshing out in the future.

BOZANIC: Phil Short will now talk about differences and perspective in the use of rebreathers for technical diving and for recreational diving.

SHORT: The recreational/technical environment is pretty much split into two. There is the rebreather for the sport or recreational diver (type R) and the rebreather for the technical diver (type T). The common ground is that these divers are hobbyists. Diving is often what they want to do with their free time. One can evolve into the other. A recreational diver who gets more involved in his sport can move on. The goal here is to focus on similarities and key differences between the two.

Training concerns of the recreational diver: Sport divers typically make infrequent dives — two or three vacations a year, with occasional dives in their home region. Statistically, keen recreational divers often do only about 20 dives a year. It is a very different level of discipline and commitment from that seen with technical diving. The diver requirements: direct ascent diving, no overhead environments — caves, wrecks, mines, or under ice — thus giving the diver the ability to ascend straight to the surface in the event of a problem. A key point is that recreational divers often go out for a couple of hours in the morning to dive and come back and spend the rest of the day on other things. The equipment should be simple to set up and use. Effectively, it just works on its own pretty much straight out of the box. Simple to use in the water as well, eliminating the need to be concentrating all the time on the machine.

Recreational diver problems and solutions again require simplicity. There should be limited choices in the event of equipment failure. Just a simple go, no go. Green light, and you can keep swimming and enjoy your dive. Red light, and you initiate immediate bailout. In the bailout scenario, the diver can just come straight up. The question has been raised about whether the diver who will have to bail out to open-circuit must be an open-circuit diver. Some agencies are already training on rebreathers as a first experience. Others maintain that they need to be qualified on open-circuit first. So is open-circuit training a required prerequisite to dive a recreational rebreather? Obviously, there are some complexities with the open-circuit state. For example, the buoyancy issues of a rebreather need to be dealt with.

The technical-diving environment is really an extension of the recreational-diving environment. These divers were recreational divers once. They just got to the point that diving became their key hobby, some taking it to the point of obsession. You have seen some excellent talks of people doing amazing projects for fun. Technical divers will be more disciplined because they are putting more time in. They will spend more time practicing the skills and diving the environment on that set of equipment. What changes the environment to make it a technical dive? Regarding environmental concerns, depth becomes logistically simpler and in many people's opinions safer because you have more time to deal with unforeseen events on CCR. Overhead-environment-diving is challenging; frequently, no matter how far you go in, you have got to come all that way back out. So it is a really important environment. With rebreather capabilities, a technical diver may need to able to deal with the situation while staying on the loop. Bailing out to open-circuit can become extremely complex. Technical divers require multiple options to problem-solve and remain on the rebreather. If a diver is very deep on some of these dives or very far in an overhead environment when the rebreather fails, then previous open-circuit skills, including multiple gas mixes, gas switches, and regulator replacement become critical. Motor reflex is important. Ultimately, there are a lot of complex issues to compare between recreational and technical areas.

BOZANIC: We are now going to hear from Nancy Easterbrook regarding supervision.

NANCY EASTERBROOK: We have a dive center in Grand Cayman that has been around for 20 years. We support open-circuit and rebreather divers, recreational and technical. We run a couple of boats and fill around 30,000 tanks a year,

Figure 2. RF3 pool tryouts. Photo by Jill E. Heinerth.

several thousand of those rebreather tanks. We started with Draegers around 1995 and grew up with a variety of semi-closed and closed-circuit rebreathers on the market.

The topic today is how we create safety in our environment for rebreather divers who visit us. One thing for sure, whatever I know right now is going to change by tomorrow. It is evolving and ever growing. We see three key elements. Foremost is the preplanning before the guests arrive. Then the prevention stage and finally the management. As a dive center receiving a wide range of equipment, experience levels, and training-agency certificates, staff training is critical. Preplanning becomes evident when guests make a reservation. The right information must be gathered. We use checklists for this. If a guest is booking in for a difficult dive vacation, this is really important. We may only see these people once every year or two, and while safety is paramount, we have to remember that they are customers and are coming to have fun.

We start by confirming the system. If open-circuit, air or nitrox. If a rebreather, what kind, so we have the right consumables available for them. It matters what kind of tanks they need. I have to ask that now. It used to be easy, but with the variety of rebreathers now on the market and travel frames you can find an array of tanks. We do not want a guest used to diving on steel getting aluminum. Such issues can be important to safety and comfort. The next step is to confirm certification level, training agency, and desired profiles. We have to be able to create this matrix of certification level, required diluents, offboards, and depth limits. We then need to assign staff appropriately for the dives. It quickly becomes complex. We are all for any kind of standardization.

The next point is to be ready for guest arrival. If a rebreather diver is coming in late, it is not like an open-circuit diver. They want their scrubber. They want their gases. They need to analyze their tanks. They need to do some logging. So we have to factor time differently for rebreather divers to try to make it enjoyable and take the stress off of them. Prevention includes several steps. One is the waiver, confirming total dives and last dives, and certification dates. These are all good indicators. The orientation follows. It is important to really show guests where things are. One example of that might be the scrubber. For example, a customer came into the shop recently and asked for some ExtendAir® cartridges. Staff said, "Certainly, they are right over there." One box said large bore, the other says small bore. The guest did not realize there were two. We learned the lesson that large and small was not good enough. Now its "Use only with Titan," etc. The variety of consumables can become a safety issue. Guests may not be used to having as many choices as we have to support different units.

There is a quiet observation during equipment setup. We maintain a triage area to make it easy for setup and simple maintenance. This is also a good place and time for quiet observation. We have a chance to get a feel for level of experience, equipment, and configuration. I always say, "Do not be afraid to ask. We do not know everything." This is an important time to try and prevent problems before they arise, before we get in the water. That is what I was taught as an open-circuit instructor, and it seems to work well for rebreathers.

The last piece is the management during the dive, how to put buddy teams together, matching divers to run safe profiles. Advance discussion of emergency procedures helps a lot. In-water supervision is important, with the right staff assigned, observing divers as much as possible.

So the resort perspective. Know what your customers need before they arrive as best you can. It is helpful to have up-to-date copies of all manufacturer operating guidelines and training standards. It would be great if those could be available online. It may be I have not seen it for six months. Maybe I am not a National Association of Underwater Instructors (NAUI) instructor, but my customers are arriving with NAUI cards. Clear labeling is very important. The checklists that we have are very important. A dive center operations checklist would be a very useful tool for new people getting into the industry.

BOZANIC: I am going to talk about key procedural issues. The first concerns are recreational vs. technical use. In my mind, it is not an equipment-based feature. The same equipment is used by recreational and technical divers. It is response-based. What do you do if you have a problem? In my mind, recreational divers should be trained to go straight to bailout. Technical divers should be trained with options to allow them to continue the mission. As Phil Short pointed out, you may not be in the best position to bailout right away. The second concern is training. You want to minimize the variety of approaches expected at the recreational level. And you want to ensure that everybody has adequate bailout to be able to get to the surface in the event of a severe emergency. Finally, regarding recreational use, there are vestiges of technical training skills that run rampant in recreational training programs. For example, running a lift bag from midwater for decompression does not belong in entry-level recreational training in my opinion. The next thing, again as Phil Short pointed out, is that we will have activity hiatuses that will require refresher training, perhaps most with the occasional traveler that Nancy Easterbrook described. Regarding supervision, I see no difference in rebreather dives and open-circuit dives. The goals are the same: to assess the skill level and competency of the divers and then to make the experience as safe and enjoyable for them as possible. I do not think we need a lot of different protocols for rebreather divers versus open-circuit divers. Checklists we do need. The problem is that those of us who are considered role models in the industry rarely use them. The same thing is true in many other aspects of the industry. For example, we all tell people to keep a logbook. And yet, we come up here, and Neal Pollock finds it a noteworthy instance that Phil Short has truly logged his 6,000 dives. Everybody in this room should be able to hold up a logbook that says I have done X number of dives. I see the same thing with rebreather checklists. Part of it is because the checklists are not well written or are hard to use or they contain unnecessary steps. The other issue of checklists is that people put together the rebreathers for use, then they only do part of their checklist because they are not going to be diving until later that afternoon or the next day. One of the recommendations I would make is that we use an established, industry-wide immediate predive checklist that is simple, quick, and able to address most of the problems that we see as direct causal agents in accidents. I am talking about a two-minute checklist that everybody does immediately prior to jumping in the water.

I use an eight-step checklist for my training programs and with my clients (Figure 1). The first step is verifying that all the gas supplies are on. You do it by running the automatic diluent valve (ADV) or running the manual inflation buttons while observing the oxygen and diluent submersible pressure gauges (SPG). A drop in either indicates that the cylinder associated valve is not completely opened. Do not check this by manipulating the cylinder valves. It is too easy to inadvertently turn off a valve instead of turning it on. Verify that the bailout supply is functional and that the buoyancy compensator (BC) is functional. Verify the electronics are turned on and the heads-up display (HUD) is functioning. Check that the PO_2 in the breathing loop is at least 0.4 atm. Prebreathe the unit. Confirm that the sensors are functional and responding. Confirm that the solenoid is functioning, adding oxygen in electronic closed-circuit systems when it is supposed to. Verify the mouthpiece position and where it is. And finally, verbally confirm that a bubble check will be completed immediately upon entering the water. This whole thing takes two minutes.

1. Verify all gas supplies are on.
2. Verify bailout supplies are functional.
3. Confirm BC is functional.
4. Verify electronics are on and HUD functioning.
5. Confirm PO_2 is at least 0.4 atm.
6. Prebreathe for one minute.
7. Verify mouthpiece position.
8. Bubble check.

Figure 3. Bozanic immediate predive checklist.

Regarding solo diving, we recognize that there is a risk over buddy diving. But it is common in technical diving and recreational diving and is often demonstrated by our role-model instructors, because they are the ones doing most of this. They are jumping in the water to check anchors by themselves. So everyone says, "I am not supposed to dive alone, but Joe over there does it, and he was my instructor." The reality is we need some kind of a reasonable position that is something other than, "Just say no," which we know does not work. I am throwing out a number — 100 hours on rebreathers before you think about going on a solo dive for whatever purpose.

The other issue that I want to talk about is going too far too soon. This is the primary reason that many experienced open-circuit divers have died on rebreathers. They are very confident doing 300-ft (91-m) dives on open-circuit. They get trained on a rebreather, and 10 days later they are trying to do the same depth on a rebreather. People are progressing into advanced environments before they have built the muscle-memory or skills to be ready. Dave Conlin pointed out that they made an institutional decision to use the rebreathers on every dive for 18 months. That is important to be able to dive safely. The problem is that training agencies only require 25 hours of time, which in my opinion is insufficient time to be ready to participate in advanced diving activities.

Forrest Gauthier will now talk about science versus opinion.

FORREST GAUTHIER: How many of you have participated in chat rooms and bench discussions that confused science and opinion? We can look at what science and opinion really are to see if we can separate them. According to Isaac Newton, science is a method of inquiry based on a gathering of empirical, measurable things that can be calculated as evidence. All this really means is seeing something with our eyes and proving them with our calculators. So what of opinion? According to Webster, opinion is a view or judgment formed about something. But then it gets complicated. It is also a belief or view shared by a large number of people about something. So if we all have the same opinion, it must be true? No, but before we start bashing opinions, we must remember that opinion is arguably a step of science. Without seeing, we do not begin to form an opinion, and seeing is the first step of the scientific method. Remember that which is observed. The discipline of scientific method, however, is to use our intuition to guide our efforts not to establish an opinion. Our intuition is often right, and as divers we frequently depend upon it. But it can also be wrong. The larger danger we face in our community is that our opinions often set policies simply since large numbers of us hold the same ideas. Sometimes such policies are wrong. As an example, some of you may remember when nitrox was leaked into the recreational dive community. Oh, boy, did the opinions fly then. Who can remember, "Just say no to nitrox?' It was a popular opinion that was wrong. It slowed the acceptance of nitrox.

The effect of every error, quirky problem and wrong opinion we propagate now is multiplied over time. With this in mind, let us have a discussion about what popular opinions that we should probably replace with hard, reproducible science. We might start with oxygen cell life. Oxygen cells are deterministic devices. It is one molecule in and four electrons out. Why can we not establish processes and procedures that can give us more reliable and predictable life, be that in-water testing, surface testing or some guidance from the manufacturers?

Scrubber duration is another challenge. CE testing generally describes about 60 minutes of dive time per kilogram of scrubber. But the industry standards for scrubbers is supposed to go 140 L of CO_2 per kilogram. Most of us are diving our scrubbers longer than the certified time. Why do we not have better information from the manufacturers, possibly tables that give us a variety of parameters to minimize our guesswork? Another example is unit assembly and testing. When I first learned CCR, we were taught the bagpipe test to look to see whether or not our scrubbers had integrity. You can assemble the scrubber wrong, do a bagpipe test, and it will pass. We also have the same issue with partial pressures. We have a lot of research on oxygen partial pressure, toxicity, pulmonary and cerebral, but most of that research was not done for CCR diving. We really do not know the proper half-life of superoxides or free radicals, and yet we are living within those environments. We need better information to make that happen. Jeff Bozanic touched on prebreathing the rebreather. I am not talking about preflighting, and I am not talking about a Zen moment. When we are prebreathing our rebreathers, what are we really accomplishing? The manufacturers tell us that the scrubber works at the existing ambient temperature. Are we testing it for CO_2? Have you ever done the calculation to see how long you would actually have to feel that? And then after the dive, what can we do to really manage after the dive processes better? How often and with what should we clean the loop? How do we know if it is clean? And then what do we do with the leftover scrubber? If we seal the canister hermetically, will it last for months? A year? Are there any issues we need to know about? We need proper answers. How about O_2 cell storage after the dive? We are all told by the manufacturers to keep them cool, in low oxygen environments away from vibration and shock. What is the proper procedure? Should we put them in the refrigerator? Should we short the pins to keep gas from building up? These are all things we need to know. And our guesses are not sufficient. With this in mind, I hand it over to Danny Graham for some preliminary research addressing some of these issues.

DANNY GRAHAM: I am the production manager for Nuvair Compressors out of California. I have also been diving since 1973, initially as a commercial diver harvesting sea urchins. I started diving rebreathers in 2008, and I currently dive an Evolution Vision. Two weeks ago I got an in-the-loop CO_2 monitor from DE-OX in Italy and installed it in my unit. Jeff Bozanic asked me if I would do a little bit of research to present at this panel (Graham and Bozanic, 2013). He proposed this question. Is there actually any value to a full five-minute prebreathe? He gave me a little process to work on. Take a small group through a five-minute test, removing the scrubber from the unit, give them a small path to controlling the PO_2 at 0.7 and take readings from the CO_2 every 30 seconds of the test, checking to see that each of them stays cognizant and able to control that PO_2 at whatever levels they are at. I was able to observe a breathing change as the CO_2 built up, but not one of the subjects noticed their own breathing increasing. We heard this yesterday; you do not notice when you are having CO_2 poisoning. Your body just simply tries to breathe faster to eliminate the CO_2 buildup. Each of the subjects pegged the CO_2 analyzer at 5 percent by the three-minute mark. No one felt any distress at four minutes; 78 percent felt no distress at the end of the test; 14 percent reported low-grade distress at the end, typically lightheadedness; 7 percent reported possible distress, a little something but nothing sure. I offer no conclusions, I am simply giving you ideas and these questions. If individuals may not feel distress with no scrubber and CO_2 levels significantly higher than we think is OK, will they notice a missing o-ring or poor seal in a scrubber? Will they notice not having their own seal? Will they notice anything whatsoever?

BOZANIC: I am going to consider rebreather cleaning post-dive. This was a project done by my 14-year-old son for a science fair project (Bozanic and Bozanic, 2013). A lot of work that could be done does not require a major laboratory. We do not have any data to suggest that cleaning is a problem or not a problem beyond anecdotal reports of people getting unknown respiratory ailments after rebreather dives. Is it from the rebreather, or is it from something else? We do not know, but cleaning may be an issue. People believe the absorbent kills bacteria. Many just rinse the gear with fresh water. Others clean after a week of diving, some after a day. Some use spray disinfectant, others use ozone gas put through the loop. There are many procedures taught by both manufacturers and instructors, but no literature fairly evaluating the efficacy of different cleaning procedures. Disinfectants, Virkon, RelyOn, betadine, alcohol, Listerine, a whole slew of them, none with documentation of efficacy.

We decided to look at what could be done to differentiate effectiveness. The hypotheses were that some of these probably work, and some of them probably do not work, and that there are some things we could probably do better even if we do not know what. We used Titan rebreathers to complete 30- to 40-minute dives. We took swabs from multiple locations in the loop, the mouthpiece, the exhalation hose, and the inhalation hose after the scrubber. The swabs were transferred to agar plates, incubated at two days, and a colony count completed. We report on a very limited number of trials. There was a lot of growth on the culture plates after doing nothing. Fresh water rinses knocked that down by 50 percent but was largely ineffective. One issue we faced was that we observed some inconsistent results. As an example, we noted that of eight Steramine trial swabs and cultures, seven were completely clean, with one exhibiting significant growth. We did not know if those outliers reflect methodological problems or true effect." then continue with the sentence "We decided to remove one outlier. We found that all of the disinfectants worked much better than doing nothing or a fresh water rinse alone. It is hard to see differences between disinfectants. We looked at three ways different disinfectants were used: spraying then waiting 10 minutes before a fresh water rinse; rinsing with a mix of disinfectant and fresh water; and filling the loop with disinfectant solution allowed to stand for 10 minutes before a fresh water rinse.

Spray alone with RelyOn resulted in a lot more growth than any of the rinsing protocols used elsewhere. We think the surfaces were not getting coated quite as well. The next thing is if you will look at disinfectants specifically, these are the flood and rinsing methods, and if you look at the colony counts, we are now in the tens as opposed to the hundreds of thousands. So you see that there is a huge improvement over what is going on. This is not a definitive study. We do not know why the outliers were there. We know some of the bacteria that we were culturing, including pseudomonas and *E. coli.* We do not know how many are harmful. We did not assess the impact of the disinfectants on the equipment or materials themselves. We did not know whether increased trials would produce equal results. What we find is that doing nothing is bad; fresh water rinses are inadequate, but they help; and full floods tend to be better than spray procedures. These findings are consistent with what most of us in the industry, I believe, are teaching right now.

GAUTHIER: The reality is that many of the processes, procedures and opinions that we now follow may not be as scientific or evidence-based as we need. I believe that we can do a better job looking to scientific methods to find the best answers for our sport and assuring ourselves that we are training the next generation of rebreather divers in the best processes for safety.

BOZANIC: We are going to conclude this session. We have tried to show you that there are things that can be done operationally to make rebreathers safer to use and also that there is a lot of opinion out there that needs to be superseded by science.

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Figure 4. Carrie Kohler always carries adequate bailout. Photo by Richie Kohler.

REBREATHER CLEANING EFFICACY

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ABSTRACT

Titan® rebreathers were used for 30-minute dives in normal operation. The rebreathers were then treated using a variety of protocols, including no postdive cleaning, postdive drying only, freshwater rinse, and application of RelyOn®, Listerine®, Betadine®, or Steramine® disinfectants. Based on procedures currently used in closed-circuit diving operations, disinfectants were applied using one or more of three methods: spray application, rinse through, or flooding. They were then swabbed in four locations (mouthpiece, exhalation hose, exhalation counterlung, and inhalation hose), the swabs cultured for 48 hours at 35-37°C (95-99°F), and individual colonies of bacteria either counted or estimated. Outcomes indicate that failing to wash rebreathers after use resulted in confluent (>100,000 colonies) colonial growths. Growth resulted from swabs in all four locations, including post-scrubber sampling points. Growth was seen even after allowing rebreathers to dry for two weeks prior to sampling. Freshwater rinsing reduced colonial growth to an approximate 30,000 colonies per culture. All disinfectant applications reduced colonial growth from 0-3,500 colonies. Application procedures varied in efficacy, with the following methods ranked in increasing efficacy: spray, rinse, flooding. The most effective combination tested was the use of Steramine® floods, with zero postincubation colonial growths seen. Based on these results, the authors conclude that rebreathers should be cleaned after use and that some type of disinfecting agent used.

Keywords: bacteria, closed-circuit, contamination, disease, disinfect, illness, sterilize

INTRODUCTION

Closed-circuit rebreather (CCR) use is becoming increasingly common in the recreational-diving community. Since the mid-1990s a wide variety of models and types of rebreathers have been utilized. All of these differ from more commonly available open-circuit (OC) scuba equipment in that exhaled gas is circulated through a closed system, called the breathing loop. Carbon dioxide is removed using a soda lime (calcium hydroxide) absorbent, oxygen is added to replace what was metabolized, and the gas is reused by the diver. One equipment factor that is different between the two types of equipment is that the internal surface area of CCRs is much greater than OC equipment and much less prone to rinsing by water in which the diver is submerged. Contamination of these internal surfaces by the diver is consequently greater in CCRs than OC.

When the diver exhales into a rebreather, germs from the mouth and respiratory system, such as *Streptococcus salivarius*, Spirochetes, and *Lactobacillus* sp. (Todar, 2011) are distributed throughout the unit. This biological contamination of the breathing apparatus may lead to infections during subsequent use (Anon, 2010). Another concern is that a single rebreather may be used by more than one diver in a given day or period of time. This leads to a risk of bacterial cross contamination between individuals (Bozanic, 2010).

Anecdotally, many rebreather users have complained of low-grade respiratory ailments (Howard, 2013), including coughs, colds, chest congestion, and similar problems. It is uncertain whether these problems are related to rebreather usage. In at least one case, a severe fungal infection of the lungs was attributed to rebreather use (N. Bailey, May 2012, pers comm). The course of treatment took more than nine months.

In a parallel case, a professional musician contracted a similar fungal infection after playing a set of bagpipes that had not been disinfected after prior usage (T. Howard, March 2013, pers comm). The pipes in question had been stored for several months since the previous use.

After using a rebreather, experts recommend some type of cleaning regimen. Different manufacturers recommend chemicals such as Betadine®, RelyOn®, Listerine®, and bleach. However, these regimens differ significantly. No studies have tested or validated standards for cleaning rebreathers used for underwater breathing.

The closest example to a rebreather in common usage is an anesthesia machine. Though research on cleaning rebreathers is lacking, many studies have done on anesthesia machines (Baillie et al., 2007; Browne and Chernesky, 2011). Anesthesia machines and rebreathers are similar in that both are closed-circuit systems and both use soda lime to remove carbon dioxide. The absorption of carbon dioxide by the soda lime is an exothermic reaction that causes the air in the loop of the machine to become warm and moist, producing an environment conducive to bacterial and viral growth. A variety of organisms have been found in previous studies involving anesthesia machines, such as *Candida* sp., *Dermatophytus* sp., Penicillium sp., *Staphylococcus, Pseudomonas*, and *Mycobacterium tuberculosis* (Maslyk et al., 2002; Arai and Azevedo, 2011). It used to be thought that the soda lime in the carbon-dioxide absorbent bed would kill the bacteria in the breathing loop, but Leijten et al. (2011) found that soda lime had no demonstrable bactericidal action. Procedures for cleaning anesthesia machines have included disinfection, steam sterilization, disposable parts, scrubbing and the incorporation the hydrophobic membrane heat and moisture exchanging bacterial/viral filter (HMEF) (Rathgeber et al., 1997; Hogarth, 2011). Many of these cleaners are not available to the general public nor is it possible to have autoclaves in one's home. Last, the incorporation of an HMEF has not been possible in rebreathers used as an underwater breathing apparatus (UBA) due to the structure of the rebreather itself.

The purpose of this project is to find a chemical cleaner and procedure that is effective at preventing bacterial growth in closed-circuit rebreather UBAs.

CURRENT DISINFECTING PROCEDURES

Rebreather divers utilize a variety of methods and agents to clean their rebreathers. A brief summary of the more common of these follows.

Nothing. Some divers do not clean their CCR. The rationale is that the scrubber material (calcium hydroxide) is extremely alkaline and kills any germs, fungi, bacteria, or viruses that pass through it. They further postulate that adequate internal drying of the rebreather components between usages will kill organisms that might cause infection.

Freshwater rinses. A step beyond doing nothing utilizes a daily freshwater rinse. Freshwater rinses are done by flushing clean water through the hoses of the unit and filling and draining the counterlungs one or more times. The belief is that a thorough freshwater rinse is adequate to flush any contaminants or biological organisms from the equipment.

End-of-trip wash. Some utilize their rebreathers during multiple consecutive days (up to six days of use is commonly reported) and then clean them at the end of the dive sequence. Their opinion is that any growth is not harmful, because insufficient growth occurs during short intervals when the equipment is used during consecutive days. They further argue that since they are the only person using the rebreather it is only their personal flora and fauna to which they are exposed and thus is not a safety issue.

Daily disinfection. Some divers maintain their units by cleansing them daily, usually with some form of disinfectant. Many methods are used, generally falling into two main procedures: spraying internal parts of the components with a disinfecting agent followed by a freshwater rinse or soaking the components to varying degrees with a disinfecting agent.

Cleaning Agents. Different disinfectants have been used in the recreational CCR community, including RelyOn®, Virkon®, Betadine®, Listerine®, Steramine®, ORF chemicals, alcohol, ozone gas, and many others. Disinfecting agents are used in different manners: liquid solutions, spray applications, rinses or sloshing through the system, soaks, and aerosols.

RelyOn® and Virkon® are generally used by spraying hose and counterlung internal surfaces with a solution from a spray bottle and then allowing them to sit for 10 minutes. The active ingredient in both RelyOn® and Virkon® is potassium peroxyumonosulfate.

Betadine® and Steramine® are typically applied by rinsing or sloshing appropriately diluted solutions through the breathing loop components or flooding the internal volumes completely. Generally a 10-minute contact time is utilized when Betadine® is used, while immediate contact is considered adequate with Steramine®. The active ingredient in Betadine® is povidone-iodine (10 percent) and in Steramine® are alkyl dimethyl benzyl ammonium chloride (5 percent) and alkyl dimethyl ethylbenzyl ammonium chloride (5 percent) (Anon 2006).

Listerine® is used the same way as Betadine®. It has been used full strength and also in varying dilutions. The active ingredients are menthol, thymol, methyl salicylate, eucalyptol and alcohol.

Ozone gas is blown through the breathing loop of the rebreather to control growth of biological organisms.

HYPOTHESES

A CCR that is not cleaned will have more growth of biological contaminants than the CCR that is cleaned. CCRs cleaned with the disinfecting agents will have less growth than those solely rinsed with fresh water.

METHODS

Each Titan® rebreather was used for 30 minutes underwater during ocean dives. A minimum of two divers using two CCRs were used for each trial. After the dives the rebreathers were swabbed in four locations: mouthpiece, breathing hoses, counterlungs, and the inhale connection hose directly after the scrubber. The swabs were then used to inoculate sheep blood agar plates divided into four quadrants labeled with the numbers 1 (mouthpiece), 2 (exhalation hose), 3 (exhalation counterlung), and 4 (inhalation hose). Swabs were taken after an initial freshwater rinse and then again after cleaning with a disinfection agent.

The plates were placed inside sealed containers with a lit candle so that oxygen would be depleted, leaving the plates in a high carbon-dioxide environment for optimal culture growth. All plates were then placed into an incubator for 48 hours at 35-37°C (95-99°F). At that time the number of bacteria colonies was counted. If there were too many colonies to count, an estimate was made. The plates were photographed for documentation.

Staff at the pathology laboratory at Long Beach Memorial Medical Center grossly identified organisms and verified counting estimates. When there was a delay between incubation and counting, photography, or identification, the plates were maintained in a refrigerated condition at approximately 34°F (1°C) to stabilize the plates and prevent further growth.

On the first rebreather trial, three dives were conducted on a single day. Rebreathers were not cleaned (Experimental Condition #1) so that it could be determined if there was bacterial growth after sitting for two weeks or if bacteria were killed by the time period and internal component drying. Swabs using both dry cotton swabs and swabs dampened with de-ionized water were taken two and 14 days after the dives were concluded.

On the other dives, when the divers surfaced the rebreathers were transported to the test location, where they were given a freshwater rinse (Experimental Condition #2) and initial swabs taken. Sampling was done within one hour of the dives being concluded.

During two trials each, a variety of disinfecting agents and procedures were utilized to clean the CCR. These experimental conditions (#3-9) included the following.

RelyOn® using spray application. Disinfectant solution was made using five grams of RelyOn® mixed with 500 mL water. The resultant solution was sprayed into every breathing-loop opening (mouthpiece, inhale- and exhale-hose openings, and the two counterlung openings). The components were allowed to sit for 10 minutes and then were rinsed. Subsequent swabs were then taken.

RelyOn® using flood application. Disinfectant solution was made using five grams of RelyOn® mixed with 500 mL water. Breathing-loop components were then completely filled with the resultant solution and allowed to sit for 10 minutes. Swabs were taken after a final freshwater rinse.

Betadine® using flood application. Disinfectant solution was made using 4.0 mL of Betadine® liquid to one liter of water (U.S. Navy, 2008). Breathing-loop components were then completely filled with the resultant solution and allowed to sit for 10 minutes. Swabs were taken after a final freshwater rinse.

Listerine® using rinse application. Breathing-loop components were partially filled with undiluted Listerine®, which was then flushed through the system and poured out. Components were allowed to sit for 10 minutes and then rinsed with fresh water before swabbing.

Listerine® using flood application. Breathing-loop components were completely filled with undiluted Listerine® and allowed to sit for 10 minutes. Swabs were taken after a final freshwater rinse.

Steramine® using rinse application. Disinfectant solution was made using two tablets of Steramine® to four liters of water. Breathing-loop components were partially filled with the resulting solution, which was then flushed through the system and poured out. Components were immediately rinsed with fresh water before swabbing.

Steramine® using flood application. Disinfectant solution was made using two tablets of Steramine® to four liters of water. Breathing-loop components were completely filled with the resulting solution and poured out. Components were immediately rinsed with fresh water before swabbing.

Controls. De-ionized water used to produce the disinfectant solutions and tap water used to rinse the rebreathers were both cultured to rule out the water as a source of bacteria. The swabs were put under the running water, agar medium inoculated, and then the plates incubated for 48 hours.

Data are presented as mean ± standard deviation or median, as appropriate.

RESULTS

Colonial growth results for each experimental condition are tabulated in Table 1. Because the sample size was small (n=2-6 per experimental condition), the results from the swabs in different locations were treated as individual data points for each condition. Likewise, when comparing swabs from different sites on the rebreathers, all of the test conditions for an individual swab site were utilized to compare against other swab sites. These results are in Table 2. Finally, because clean laboratory conditions were limited, a single value outlier from each data series was removed to reduce extreme variability, making result interpretation more consistent.

Table 1. Average counts of colonial growth after incubation per experimental condition.

Experimental Condition	Colonies (mean)	Colonies (sd)	Samples (n)
Nothing	100,000	0	7
Freshwater Rinse	30,807	34,618	23
RelyOn® Spray	3,333	4,714	7
RelyOn® Flood	23	23	7
Betadine® Flood	10	8	7
Listerine® Rinse	11	7	7
Listerine® Flood	3	6	7
Steramine® Rinse	10	25	7
Steramine® Flood	0	0	7

Table 2. Average counts of colonial growth after incubation per swab site.

Swab Site	Colonies (median)	Samples (n)
Mouthpiece	5,280	8
Exhalation Hose	375	8
Exhalation Counterlung	135	8
Inhalation Hose	34	8

The rebreathers that sat for two weeks after cleaning had relatively little growth when dry swabs were taken. The dry swab showed confluent growth (>100,000 colonies) in the mouthpiece and minimal growth in the other swab sites. After being swabbed with dampened swabs, results showed confluent growth in all locations. These values are different from those presented in Table 1, which includes only the swabs taken immediately after diving but before rinses. The prevalent organism was *Pseudomonas* sp. (T. Chen, February 2012, pers comm).

The swabs taken from the divers' noses were variable. One diver's culture grew *Streptococcus* sp. and *Staphylococcus* sp. (T. Chen, February 2012, pers comm). The other diver's culture grew nothing.

Cultures from the de-ionized water and tap water used for mixing disinfectants and rinsing the rebreathers grew nothing.

DISCUSSION

Our data suggest that the most contaminated parts of the rebreather system are the mouthpiece and the exhalation hose. The mean for each component was utilized as a variable for trend analysis; however, only those cleaning methods that might have left significant contamination were included, i.e., experimental conditions 4-9 (disinfectant rinses and floods) were excluded. Because this trend analysis included multiple cleaning modes, standard deviations are not provided because the conditions are too dissimilar for the values to be meaningful.

However, all parts of the rebreather cultured bacterial growth after use, including those on the inhalation side of the rebreather after the breathing gas had passed through the absorbent bed. It is apparent that having breathing gas merely pass through the scrubber bed does not kill all organisms. Bacterial growth included Coliform bacteria and *Pseudomonas* sp. (T. Chen, February 2012, pers comm). This indicates the need for some type of cleaning regimen for rebreathers.

To test if prolonged storage is effective in preventing bacterial growth, two rebreathers were not cleaned after use but were allowed to dry completely for two weeks as the sole disinfection protocol. When dry swabbing was performed, there was relatively little growth. However, when a wet swab was used to sample the internal components, confluent growth resulted.

Wet swabs may have been more effective in sampling because water is slightly polar-negative and thus may have picked up more bacteria. It is important to note that the wet-swab results more likely mimic real diving scenarios, as use in water environments and the moisture generated by exhaled breaths probably also facilitate bacterial transfer. It is possible that airborne contamination may have occurred during storage; however, this is unlikely because the cultured bacteria were identical between the stored units and the rebreathers sampled immediately postdive. This suggests that contamination occurred during the dives.

Using freshwater rinses reduced bacterial growth. Average growths of approximately 30,000 colonies is roughly one-third of that seen when no cleaning was performed. However, these growth results indicate that this is an inadequate disinfection protocol.

Several disinfecting agents were tested using multiple application procedures. When compared to the protocols discussed above, all of the procedures involving the use of disinfectants were much more effective at preventing bacterial growth (Figure 1).

However, when the procedures using disinfecting agents were examined separately, it was apparent that the practice of using spray applications was less effective than rinse or flood protocols (Figure 2). When disinfectant solution is applied using a

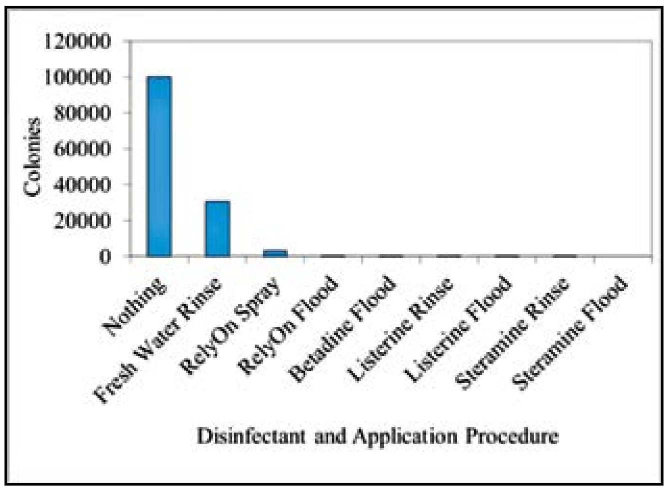

Figure 1. Average bacterial growth colonies by cleaning procedure.

spray application, the practice is to use a spray bottle like those used to apply window cleaners or typical kitchen cleaning solutions. Disinfectant solution is sprayed into all of the orifices of the breathing loop (mouthpiece, inhalation and exhalation hose ends, and tops of both counterlungs). Ten squirts are made into each opening with the spray nozzle set to spray.

There are difficulties in coating all internal surfaces in this manner. The breathing hoses are corrugated and thus are shielded to some extent from a spray applied from only one direction. In addition, the breathing hoses flex, further increasing the probability that internal surfaces will not be coated with disinfectant. Some of the openings to the internal surfaces are a significant distance (30 cm or more) from the distal portions of the component. This would include both breathing hoses and both counterlungs. This compounds the problem of adequately coating internal surfaces. It is hypothesized that these barriers to disinfectant application impairs the efficacy of spray application procedures.

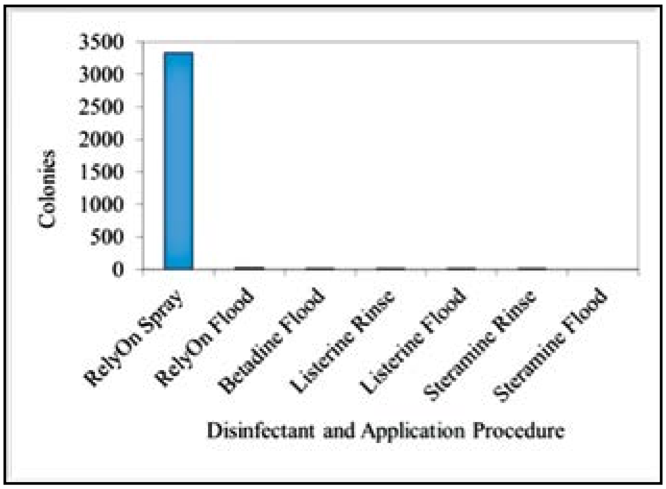

Figure 2. Average bacterial count by disinfectant application protocol.

When spray application protocols are removed from consideration, it can be seen that both rinse and flood applications exhibit similar efficacy, with flooding protocols better than rinsing practices (Figure 3) in preventing bacterial growth. In this study Steramine® and Listerine® provided slightly better results than the Betadine® and Virkon®. While all of the tested cleaners dramatically reduced bacterial growth when used with rinse or flood applications, only flood application of Steramine® completely eliminated bacterial growth.

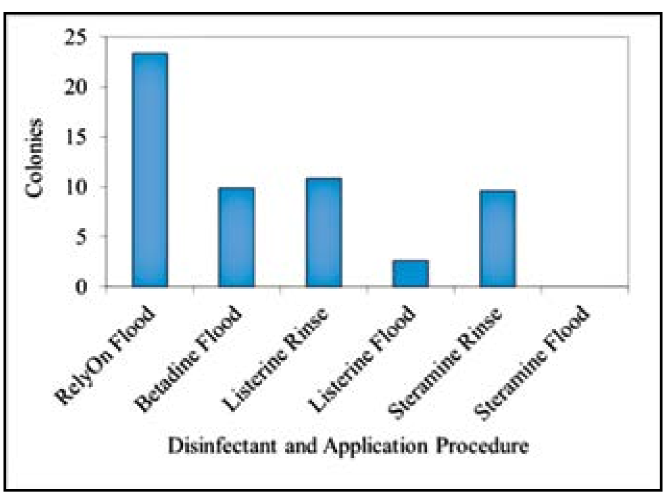

Figure 3. Average bacterial count with rinse- and flood-application protocols.

Our results were somewhat variable within each category. This can be attributed to the actual procedures used, which mirror how divers clean their equipment. With RelyOn® we used a spraying method and let it sit for 10 minutes before rinsing. The amount applied per spray probably was inconsistent, as was the angle of application. With the rinse-application procedure, the fluid was poured into and out of the hoses and counterlungs, and then the breathing-loop components sat for 10 minutes. There was never an exact volume of liquid cleaner poured into the hoses and counterlungs nor could the breathing-loop components be laid in consistent positions during the sit time. The most consistent disinfection protocol was the flooding procedure, in which the components cleaned were completely filled with solution.

Further variability might be explained based on the sites where the dives occurred. The dives took place in two different sites. We are not sure what the bacterial load was in the water at either site.

We also have insufficient repetitions within each category to make a statistical evaluation between the cleaners. This in part was due to time limitations, location, weather, and diver health issues (common cold).

CONCLUSIONS

Our data show that rebreathers do need cleaning after diving. Neither calcium hydroxide in the absorbent nor complete drying and extended durations between dive activities kills all of the bacteria in the loop. It can also be concluded that freshwater rinses are inadequate to kill off the bacteria in the breathing loop. Spray applications of disinfectants were less effective than rinse or flood applications, presumably due to inadequate coating of all internal surfaces. Disinfectant rinse applications provided better results, with the best results seen when the breathing loop was completely filled with disinfectant solutions. RelyOn®, full-strength Listerine®, Betadine®, and Steramine® all provided substantially identical efficacy when flooding application procedures were utilized, with Steramine® providing marginally better results.

FURTHER WORK

There are numerous areas in which this work can be expanded. The first is the number of replicates. Simply repeating this study to expand the number of trials may produce statistically valid results. There are many other cleaning or disinfecting agents that could be included in a similar study. These include, in part, ozone gas protocols, Enviroguard 64®, other dilutions commonly used in the field (such as 50 percent dilution of Listerine®), CaviCide®, Envirocide®, and MetriGuard®. We did not attempt to ascertain the adverse impacts of any of the cleaning agents utilized in this study on either human health or rebreather component damage. Finally, utilization of other models of rebreathers may not present identical findings, based on differing component design and structure.

ACKNOWLEDGMENTS

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PREBREATHING DURING CLOSED-CIRCUIT DIVING APPARATUS SET-UP INEFFECTIVE IN ASSESSING SCRUBBER EFFICACY

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ABSTRACT

An Ambient Pressure Diving (APD) Inspiration closed-circuit rebreather (CCR) with an incorporated carbon-dioxide (CO_2) monitor was assembled without absorbent installed and used in a dry setting by 14 volunteers each for a five-minute period. The volunteers were asked to maintain the setpoint at 0.7 atm and to terminate the trial if they felt undue stress or discomfort. An observer monitored the trials, recording PO_2 and PCO_2 levels every 30 seconds and confirming subject awareness and comfort. All subjects were observed to have increased respiratory rates, of which they were unaware. Within 3.5 minutes 93 percent (n=13) of the subjects achieved a PCO_2 of 0.05 atm (5 percent SEV CO_2) in their breathing loops, 10 times the allowable limit of 0.005 atm. All of the subjects reported no distress at four minutes into the trials. Two subjects reported minor distress, and one subject reported possible distress at five minutes. The remaining 79 percent (n=11) of the subjects reported no distress. All participants elected to remain on the breathing loops for the entire test procedure, including those who reported signs of distress, as they felt that the minor signs of distress they were experiencing were insufficient cause to terminate participation. Based on the poor correlation between actual and perceived problems in this extreme assembly failure and the likelihood that other less-extreme failures would be even less likely to result in observable effects, the authors advocate a return to a one-minute prebreathe standard during CCR predive checks.

Keywords: absorption, breakthrough, channeling, CO_2, hypercapnia, predive check

INTRODUCTION

One of the critical functions that a closed-circuit rebreather (CCR) performs is to remove metabolically-produced carbon dioxide (CO_2). If it fails in this task, rapid CO_2 accumulation in the breathing loop will lead to hypercapnia and CO_2 toxicity. To prevent this from occurring, rebreather scrubbers are tested as part of the design and validation process to determine how long they should last before CO_2 levels rise to an unacceptable level. The level deemed reasonable is 0.5 percent CO_2 surface equivalent value (SEV) or a CO_2 partial pressure (PCO_2) of 0.005 atm (Anon, 2009). Symptoms of hypercapnia may begin to manifest at a PCO_2 of 0.02, or 2 percent CO_2 SEV. Symptom severity increases with both CO_2 concentration and the duration of exposure but may include increased respiratory rates, a feeling of air starvation, panic, slowed reaction times, muscle twitching, convulsions, headache, dizziness, weakness, nausea, confusion, stupor, unconsciousness, and death (Dinsmore and Bozanic, 2013).

Other factors may also lead to an excess of CO_2 in the breathing loop. Most CCRs on the market use granular soda lime absorbent similar in appearance and form to kitty litter. Users fill, or "pack," their scrubber cartridges with this granular material. If too little material is used, then absorbent may settle, allowing breathing gas to pass through a less-dense volume of scrubber. Called "channeling," this can result in measurable amounts of CO_2 downstream of the absorbent bed. This frequently occurs from improper scrubber cartridge-packing procedures.

Improperly overfilling a scrubber assembly can also result in absorbent bed density variations. Breathing gas may flow around areas of increased density, also leading to inadequate CO_2 removal or reduced time before breakthrough occurs. Breakthrough is defined as when the breathing gas downstream of the absorbent bed has a PCO_2 of 0.005 atm or more.

Improper CCR assembly, such as failure to install an O-ring, misalignment of components, improper component installation, inadequate O-ring lubrication, or even failure to install absorbent may also lead to breathing gas partially or completely bypassing the absorbent bed. Build checklists are used during the preparation of the CCR for diving, but many users cease using such checklists once they become familiar with their CCRs. Other users may complete CCR training with an inadequate understanding of the assembly process, leading to improper assembly.

Unacceptably high CO_2 levels may also be seen if the absorbent is already spent. Most recreational dives have a duration less than that allowed by the scrubber. Community practice is to use the same scrubber fill for multiple dives, with sometimes days, weeks, or months between subsequent dives. Divers may also utilize scrubber fills for time in excess of manufacturer recommendations, with the belief that the test conditions were more stringent than their actual dive profiles. Breakthrough will occur if the absorbent material no longer has the capacity to remove CO_2 at the rate it is produced or if improper storage between dives has adversely impacted the absorbent.

Immediate predive checklists are also commonly used to assess CCR functionality just before initiating a dive. One of these steps is the practice of prebreathing. The diver initiates use of the CCR prior to entering the water and monitors a number of factors to see if the CCR is working correctly. Some of the operational elements checked include "starting" the scrubber, confirming solenoid operation, observation of oxygen sensor readings to see if they appear to be functioning, identification of mushroom valve failures, and to check for breakthrough from poorly packed scrubbers, partially used scrubbers, or gas bypass.

CO_2 absorption by soda lime is an exothermic reaction. The reaction proceeds with greater efficiency if the scrubber bed is warm rather than cold. In temperate conditions (>4°C [39°F]), this process proceeds adequately after prebreathing for 15-60 seconds (T. McKenna, May 2012, pers comm). In conditions colder than that, community practice is to prebreathe for a longer duration, although that duration has never been experimentally determined or confirmed.

Likewise, 30-60 seconds is usually long enough to confirm that the solenoid adds oxygen when PO_2 drops below setpoint and that displayed oxygen sensor values vary with oxygen injection and diver use.

The final reason cited as a reason to prebreathe a CCR before diving is to ascertain absorbent function. While this practice has been advocated for many years, the times suggested or mandated for prebreathing have gradually been increasing. Early rebreather manuals do not mention prebreathing at all (Dräger, 1996; Barsky et al., 1998). A one- to two-minute duration was generally considered acceptable in the late 1990s (Betts, 1999), with times increasing to three minutes in the early 2000s (AP Diving, 2001; Gurr, 2001; Bozanic, 2002) to some manufacturers requiring a five-minute duration before the rebreather will operate properly today (VR Technology, 2009; Bozanic, 2010; Mocsari, 2010; Raymaekers, 2010; Heinerth, 2013). One manufacturer specifically explains the benefit of a five-minute prebreathe procedure in their user manual:

"This prebreathe is NOT to warm up the scrubber. It is to determine if the scrubber and the rebreather are working properly. It gives you a chance to monitor your display system to ensure that it is working and, most important, to determine how you feel during and after the prebreathe. The prebreathe is a minimum of five minutes as this much time is required for our bodies to tell us that something is wrong. The bottom line is that this five-minute prebreathe confirms your system check has been done and that all is working." (Jetsam, 2009)

It cannot be disputed that a sufficiently long prebreathing period will identify absorbent issues. At one end-point, all scrubbers will eventually fail as the scrubber is completely consumed. However, this time may be hours before such failure is noted. The more pertinent question is, what is the minimum time necessary to identify problems? This is an impossible question to completely address. For example, in the case of a partially consumed scrubber, there is no way to ensure that a fill that lasts five minutes will not fail during the sixth minute of operation. Similarly, an improperly packed scrubber may function for a short period or under conditions of low CO_2 production but not high CO_2 production. Thus, prebreathing cannot be expected to reliably identify such issues.

So the goal of prebreathing from the perspective of identifying absorbent function problems should be aimed at identifying issues related to assembly, O-ring effectiveness, or scrubber presence. This objective has never been studied in a systematic manner but has been based on opinion and anecdotal observations.

HYPOTHESIS

Prebreathing CCRs for a five-minute period is inadequate to determine that the CO_2 absorbent bed is functioning properly.

METHODS

An AP Diving Inspiration CCR with the Vision electronics was used for the testing. It was fitted with a TEMC Bio-REB CO_2 monitor, manufactured in Milan, Italy. This instrument uses a non-dispersive infrared (NDIR) temperature compensated CO_2 sensor capable of measuring PCO_2 to 0.05 atm (50,000 ppm), with a resolution of 20 ppm. It is designed to provide data in gases with continuous flow. The instrumentation was calibrated using a standard test gas obtained for that purpose. The CCR unit was assembled normally, except that the absorbent basket was not installed. Volunteers were unaware of this. The automatic setpoint was set at 0.5 atm.

Fourteen volunteers with varying backgrounds were asked to use the CCR in a dry environment. The study protocols were not reviewed by an institutional review board (IRB), as the authors are not affiliated with an institution with an IRB, and the project was an unfunded study. However, all participants were informed of the potential risks of participation, and were encouraged to withdraw from the trials at any time for any reason. Procedures were implemented to protect the participants from harm. Research results were made available to all participants. Further, participant identities and all associated information, apart from basic demographics, have been destroyed.

During the actual CCR breathing trials, subjects were sitting and wearing nose clips. The Vision handset was positioned so that screen was easily visible to both the subject using the CCR and the observer. Volunteers were asked to manually maintain a setpoint of 0.7 atm for a five-minute duration. They were directed to indicate any signs of stress or discomfort and were advised to terminate the session if they experienced any undue stress or felt at all uncomfortable.

Setpoints were monitored by an independent observer, as were oxygen and diluent cylinder pressures. PCO_2 values were recorded by the observer every 30 seconds. The observer gave volunteers OK hand signals every 30 seconds, and the volunteers were assessed on their responses. The observer also assessed other volunteer reactions, including breathing rates and any signs of non-responsiveness or stress.

RESULTS

The 14 volunteer subjects included six non-divers, six open-circuit divers and two CCR divers. Descriptive data are found in Table 1.

Table 1. Subject characteristics (mean±standard deviation with ranges).

	Male	Female	Pooled
Number	12	2	14
Age (y)	34±11 (19-47)	21, 43	34±11 (19-47)
Height (cm)	179±6 (168-191)	165, 168	177±7 (165-191)
Weight (kg)	94±13 (77-117)	61, 66	90±16 (61-117)

During the five-minute trials, all of the volunteers maintained PO_2 appropriately. Everyone maintained an acceptable level of awareness throughout the five-minute tests.

All of the subjects exhibited increased breathing rates. However, none of the subjects were aware that their breathing rate had increased. Every subject except one pegged the PCO_2 monitor at 5 percent CO_2 (0.05 atm PCO_2) within 3.5 minutes of test initiation (Figure 1).

None of the subjects reported any degree of stress or discomfort at the checks up to and including the 4.5-minute mark.

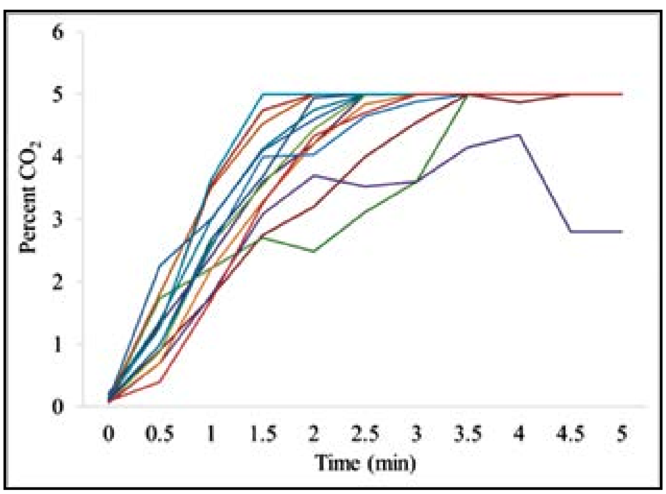

Figure 1. Breathing loop CO_2 levels.

At five minutes, 79 percent (n=11) reported no distress, two reported minor distress, and one reported possible distress. The distress reported was a slight feeling of lightheadedness. None of the subjects felt the need to terminate the test based on significance of perceived symptoms, and they opted to remain on the loop for remainder of trial period. The subjects reporting possible stress included one diver and two non-divers.

DISCUSSION

All of the subjects experienced unacceptable PCO_2 levels. Within the first minute everyone had exceeded the maximum allowable PCO_2 level of 0.005 atm. By 1.5 minutes into the trials, every subject had exceeded a PCO_2 of 0.02 atm, the level at which symptoms of hypercapnia begin to occur. One diver's PCO_2 level dropped after beginning the trial. This was most likely due to exhaling through the nose (despite the nose clip) or allowing gas to escape from around the mouthpiece. By 3.5 minutes, the rest of the subjects had reached the PCO_2 of 0.05 atm maximum reading of the device. This is at least 10 times the allowable limit of 0.005 percent CO_2 SEV. At a PCO_2 of 0.06 atm (6 percent CO_2 SEV) unconsciousness may result if that level is maintained for a sufficient period of time. It is likely that most of the participants exceeded this level, even though it could not be measured using the instrumentation used in these trials.

It is interesting to note that neither of the CCR divers reported any signs of stress. It may be that CCR divers are inured to higher PCO_2 levels, although we have insufficient data to examine this question. This suggests a question for future research.

This test was designed to mimic a worst-case failure scenario that has occurred during actual dive operations (Miller and Koblick, 1995; Bunton, 2000; Urba, 2008, pers comm; Short, 2013), failure to install a packed scrubber assembly. Any failure mode less serious than this (such as a poorly packed scrubber) would be even more difficult to ascertain, as the scrubber would be providing at least a minimal degree of effectiveness.

For a safety procedure to be adequate as diagnostic, we should expect a high correlation between the problem and problem recognition. Optimally, this should be a "perfect" correlation. In this study, only 14-21 percent recognized that there might be an issue, and that was with most extreme problem possible. Even with the recognition that there might be an issue, none of the impacted divers chose to terminate the test and cease breathing from the CCR.

One might argue that while the five-minute prebreathe procedure might not help identify any but the rarest problems, it also cannot hurt anyone. This may not be true. Longer predive set-up procedures invite violations, especially if one or more procedures, such as following predive checklists, is perceived as unnecessary or takes an undue amount of time. Such violations have been noted by both authors and seem to be a general concern within the rebreather diving community (Bozanic, 1997; Tetlow and Jenkins, 2005; Fock, 2013).

Often breaching one safety step leads to multiple violations of procedures or leads to the belief that predive checks are of little benefit to the diver. This erosion of adherence to procedure could (and might possibly be argued has) resulted in incidents in dive operations. Thus one could postulate that prebreathing should be done for the absolute minimum time needed to recognize those issues it can reliably identify.

CONCLUSIONS

A five-minute prebreathe period is not adequate for assessing proper scrubber packing, identifying gas bypass, identifying channeling or breakthrough, or identifying the presence or absence of the scrubber assembly.

While the authors did not test for other prebreathing benefits, their opinion is that prebreathing is probably beneficial for initially heating or "starting" the scrubber bed, confirming proper solenoid function, and verifying oxygen sensor response. All of these objectives can be usually be accomplished in less than a minute. The one possible exception is when diving in cold conditions, when a longer time may be necessary to adequately initiate scrubber bed reaction. This contingency has not been adequately researched.

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REDUCING REBREATHER ACCIDENTS THROUGH MODIFICATIONS TO TRAINING

Editors' note: The following text was excerpted from a transcript of the meeting provided by a court reporter. Editorial changes were made to correct grammar and remove extraneous comments. Every effort was made throughout to retain the spirit and intent of the original discussion. The session was moderated by Jill E. Heinerth and Terrence N. Tysall.

JILL HEINERTH: With between 18 and 20 rebreather fatalities per year and emerging evidence that human error can be attributed to the majority of such accidents, this session focused on examining how training paradigms might be revised to enhance a cultural shift in diver behavior that helps combat complacency. The session was broken down into discussions on the culture of rebreather diving, standards, instructor requirements and legal ramifications. Short presentations by the authors introduced the topics and challenges and were followed by an opportunity for audience input. The paper that follows includes summarized dialogue and conclusions drawn from the group consensus.

Rather than providing answers for you today, we have lots of questions to pose to you, the community, to help us arrive at some better solutions for training. We would like to look at training in a wider context. Specifically, I do not want anyone to pick on one agency or another. Instead, look at training and retention of information by divers, instructors and the culture of rebreather diving.

Yesterday Mike Menduno opened with suggesting that our industry has reached adulthood. I would say that in many ways we are still in our infancy because we are still revisiting issues that we identified at Rebreather Forum 2.0. If indeed up to 20 people a year are dying on rebreathers, obviously the status quo is not working. Let us examine possible solutions regarding learning, retention and the complacency curve.

In the last couple of days, Dr. Andrew Fock brought to our attention several different studies, including one in 2002 that examined high-risk behaviors. The decisions made by divers in those studies may have reflected the fact that in a stressful moment they may not have displayed a good understanding of physiology or perhaps a lack of practice of key skills. David Concannon urged us to look at the underlying triggers for accidents and suggested those triggers were behaviors or choices as opposed to equipment. How does that differ in recreational versus technical diving? Is automation important to us, or can we train these behaviors out of divers? Dr. Bill Stone suggested we review aviation fatality statistics, looking at the fact that in aviation, when experience is gained, that seems to lessen fatalities. Clearly that is not happening in our industry. So why are experienced divers dying on rebreathers? In his presentation he gave us a list of causes, ways to die on a rebreather, such as failure to execute or failure to detect. So choices and behaviors. Do they need to be "taught out," or are there different behaviors in training that we need focus on and improve on within our community? Bruce Partridge brought to our attention that the top causes of fatalities were poor training and poor predives. Those were his root causes. Vince Ferris reviewed his Navy Experimental Diving Unit (NEDU) investigations and tagged a large proportion of accidents to human factors. So that is what we want to focus on today. Our goals are to try to build consensus within this room and perhaps some recommendations for the future on how to move forward. We will consider four focus areas: closed-circuit rebreather (CCR) culture, standards, instructor-specific issues, and legal ramifications.

CULTURE OF REBREATHER DIVING

HEINERTH: Dr. Andrew Fock brought to our attention that experienced divers, knowledgeable divers, often have poor risk-management decisions, and complacency creeps into their behaviors. So how do we change that culture of rebreather diving to increase the emphasis on checklists? Should a greater focus on accountability be required on using predive checklists and training, and how do we make that happen? Should manufacturers be sending a checklist logbook with a purchase of a unit? Should those checklists be used for proof of currency for an instructor or a student for higher levels of training? Should agencies add a CCR educational component at all their levels of training right from entry level open-circuit (OC)? Should we place a greater focus on that buddy interaction and responsibility in a rebreather class?

TERRENCE TYSALL: Remember the previous times that we gathered together. It was contentious at times, but a lot came out of it. Pick one of these topics that means something to you. We are all the rebreather culture. I remember in the Key West swim school 10 years ago, I did a topic on technical diving then and now. We showed the difference between all the early types doing their early technical dives, becoming what was an "off the shelf" diver. I guarantee you that everybody in this room who has been on the loop of a rebreather has seen something that made them think down inside, "What is going on?" When I learned rebreathers, I learned from the military.

DALE BLETSO: Part of the culture problem, I think, is that it is always directed toward technical rebreathers rather than recreational rebreathers. Even in this forum we are still pressing technical aspects of rebreathers that really are not for the recreational realm.

HEINERTH: That is a really good observation. Obviously, the training situation is very different for the recreational diver who must bailout as opposed to the technical CCR diver who has to be trained in many different options and behaviors to react to a situation and potentially stay on the loop.

TYSALL: One thing that I am going to add is that 19- or 20-year-old divers are not out there buying $7,000 and $8,000 rebreathers. We have confident, financially secure people purchasing these things. And these are alpha personality types who are not used to being told what to do. We must address the culture of rebreather diving.

PETE MESLEY: From a cultural seed coming from an instructional background, I think it is our obligation as instructors and instructor-trainers to lead from the top. If we are doing it 100 percent of the time, then it can more readily move down through the ranks. If we follow proper rules and procedures every time we go diving, I think there is a glimmer of hope.

HEINERTH: I think you are absolutely right about leadership. There have been many analogies to aviation made this weekend. I have heard people say you cannot make people do this. Well, apparently you can. Because in aviation people buy expensive airplanes, and they still have to have a mandatory number of takeoffs and landings each year and stay up on their paperwork and checklists to maintain their pilot's license.

TYSALL: Let me tell you, checklists are amazing. The U.S. Parachuting Association is another analogy to the Federal Aviation Administration (FAA) for successful checklist use. The systems-based approach like you see in the military has the dive supervisor up on top running everything: brain on the top, muscle on the bottom. But you see as these projects get more complex, the default shifts back to checklists because so many things need to be considered.

TONY HOWARD: I would like to be a little bit controversial because I think we have used the word "complacency" with divers, and I think that in a lot of cases that is not appropriate. I would also like to take small issue with one of the positions that was mentioned recently relating to delivering pilot training and diver training. You take someone through pilot training from scratch. They have never done it before, never been in a cockpit. Not the case with diving. Divers can often go into a store and buy the gear without proof of certification. People can buy enough equipment to jump in the ocean and kill themselves whether it be open-circuit or closed-circuit, makes no difference. We also have another issue with closed-circuit diving or any technical diving because our demographic is not to take someone off the street who has never dived and stick him on a rebreather. These guys are mostly people who have done years of open-circuit diving. Their mentality, their muscle training, all their drills are all based around open-circuit diving. And if they have been a diver for years, OK, they are going to do the course, and most of them will get through the course because they understand the physics of diving. They understand partial pressures. But when things go wrong in the water, old habits come back. That is partly our fault. If you take someone who has never dived before, it is probably easier to train them. Retraining is hard. I think complacency is the wrong word. As far as training goes, we have a bigger task load with experienced divers than with non-experienced divers.

TYSALL: If I have a mantra on teaching closed-circuit, it is that this is not open-circuit scuba anymore.

PAUL HAYNES: There are two groups that need to be influenced. There is the "old and bold," which is a hard job, and then there is the "future generation," which is the recreational diver. I think the general consensus here is that checklists are extremely important, but who sees that checklist? Just the diver? Take a leaf out of an operational regime. That checklist gets prepared by the diver and signed off by the supervisor. So try and migrate that into the recreational-diving world. If it is a new generation of divers, do we present the checklist to each other as buddies and go through it? Do we ask for the checklist to be presented to us on the dive boat? Do we sign off on each other's checklists?

HEINERTH: That is a really good observation. I will admit that some of the standard operating procedures (SOPs) we use on expeditions are more stringent than what we use in our day-to-day diving. Should they be? No. So that is a cultural change. I remember back to a day on a dive boat where I had a rebreather failure just as I was standing up to jump off the boat. I immediately sat down and said, "Sorry guys, I guess I am snorkeling today." All of the experienced rebreather divers around me started to convince me that the problem I was experiencing was minor. I looked at my colleagues and friends and said, "If there is one thing you are going to learn from me, it is that I do not jump in the water with something that is already broken." I now reflect back on that day five or six years ago, and two of the people in that boat are dead. I think we have to stand up and say something. Are you using a checklist and encouraging that behavior with your buddies?

HAYNES: It should start with the instructors. Induce this process of checking each other, elevating the importance of checklists and the responsibility to each other.

TYSALL: When I finally held my own rebreather in my hands, of course, like all of us in this room, I wanted to use that thing everywhere. I want to use my rebreather because it is far more efficient, but sometimes it is just not the right tool. We need to understand that this is just another tool, not a platform that makes us better than other people.

GARETH LOCK: We talked about collection of data, and it is really important. Divers Alert Network (DAN) has a non-fatal incident reporting system. I would look out in the audience and say pretty much everyone has had a safety-compromised event that other people could learn from, and that culture of reporting needs to be driven by the agencies of the world. Again, lead by example. There will be things that go wrong on those training dives. Instructors should sit down and fill out the incident report for DAN and get that information out there.

HEINERTH: It should not be the individual's dirty little secret. You are right.

MARK POWELL: There have been quite a few comments about taking military checklists and putting them in diving. It is not going to work. It is a different environment. I would like to take a different approach. If you look at things like smoking and drinking and driving, people stopped doing it when it stopped being cool. We need to make following the rules cool. If you want to get someone to use the checklist, this is a cool thing to do. That is how we will change the behavior.

HEINERTH: I think that is incumbent on all of us as role models to put that out there.

RON ZELT: With a background in education, I can tell you that changing a program is very much like changing the culture, it has to start with the perceived need and an actual need. If you take the data we have learned in the last week and suggest the deaths we have seen prove an actual need for change, we can only enact change if the perceived need for change is there. If we as a group say the perceived and actual need are there to change, that is the initiator of change. It really starts at the bottom. When we all started in our open-water class, we were little sponges absorbing everything, and we modeled ours after our instructors. If we are convinced that the buddy system is important, we will use it. Problematically, we then see the elite in our society diving solo, compromising the lesson.

UNIDENTIFIED SPEAKER: There has been talk of developing rebreather clubs. Perhaps that would be a nice mechanism. Club bylaws could mandate the proper use of checklists.

TYSALL: I have a six-year-old at home who is an in-water animal who wants to learn to dive this summer. I want honest opinions. Should I train this kid on closed-circuit first or open-circuit? What about 12 or 13? What about 18?

LOCK: What is the mindset of your son?

TYSALL: He is a rule follower, and in kindergarten he is reading on a fourth-grade level. He is intelligent. I am curious and honestly just doing this to spark a little debate. Hands up if you would train him open-circuit first. Sixty percent. And let me see my brave rebreather people. Who would train their kid on rebreather first? A few.

RICHARD WALKER: In specific regard to that question, there is evidence as to how that probably should be done, not from the diving world but from other worlds. Fundamentally,

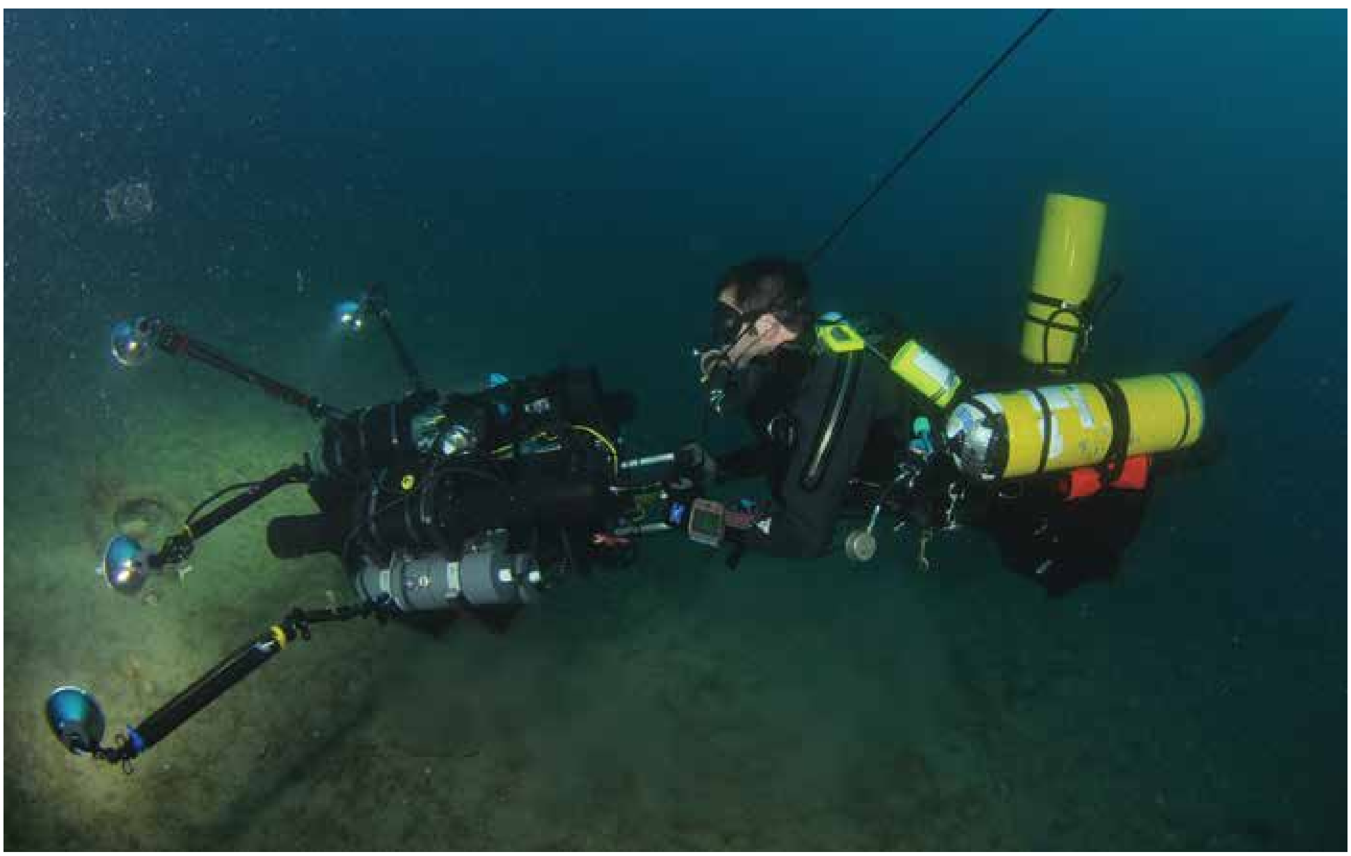

Figure 1. Evan Kovacs on the Britannic *in 2009, diving a homemade sidemount CCR modified from a PRISM. Photo courtesy Richie Kohler.*

there are two factors to consider with that in terms of him being new and being trained. One, who will he be around? Two, what modality will he depend on if his primary system fails — open-circuit. That is the common bailout pathway for all technical and recreational rebreather drivers with current technology. There is good evidence from other worlds that you should be extremely familiar with your bailout modality, so its use is fundamentally ingrained. This is the building of the base of the pyramid. As an extreme example, when something goes wrong 4,000 feet back in the cave, there should be no drama to bailout and complete the dive on open-circuit.

From a scientific standpoint, the fact that there has never been a checklist found on a dead rebreather diver may or may not be relevant. But what is known from scientific research is that no matter how high functioning the individual or individuals may be, checklists reduce error rates. And there is evidence to support that human error contributes to many of the rebreather accidents we have seen. It is very reasonable to say this particular intervention should reduce incidents and fatalities on rebreathers. It is important to stick to known facts if this body is going to promote policy to move forward.

MARTIN SAMUELSON: I think checklists will work, but probably only for the first 20 or 30 dives. It is at 40 or 50 dives when the instructor's words are not ringing in the diver's ears quite so loudly. So I came back to something Mark Caney said earlier on how much can we engineer into the rebreather so these checks are automated. I think for the recreational community that is a more appropriate way to go.

HEINERTH: To summarize this section, we must reinforce how important it is to use checklists, to do a full and proper five-minute prebreathe, and to not jump in the water with something that has not passed on your checklist. Those three things will probably prevent a vast majority of accidents.

REBREATHER STANDARDS

TYSALL: Time to shift to rebreather standards. Should we demand that the training agencies publish their standards? I was having a discussion with someone earlier, and I was not aware that I had been violating training standards by sharing those standards with my students. That is typically something I review with my students. How can we create more informed students? Again, to stimulate discussion, do you encourage academic-only training classes for students? Can somebody get on there and learn before they buy? Early experience can be a great way to get people excited about stuff.

Should the rebreather industry, which means the manufacturers, and us, the training agencies, create more stringent guidelines for the training of rebreather divers? We are going to discuss legalities here in a little bit. None of these facets of this puzzle operate on their own. They do not exist in a vacuum. And then what issues are we facing in recreational CCR training? Jeff Bozanic and his panel mentioned several. Can new divers effectively learn CCRs without open-circuit training? Is that a route that the agencies are going to take? What bailout volumes are required? And then what happens to students when they go to a resort? Should qualifications, requalifications, and minimum annual dives be required? Should resorts be coached on how to screen someone? Should there be industry standards for currency and/or a database for divers?

HEINERTH: One of my pet issues is that copyrighted standards are not permitted to be published or shared. I would like to see them more available on the Internet so that people such as Nancy Easterbrook at Divetech have the tools she needs to know what a particular card means when a person gets to her resort or so that I as an instructor can send the information to my students so that they know exactly what to expect on their course.

MARK CANEY: Regarding standards, we [at the Professional Association of Diving Instructors {PADI}] certainly have no secrecy concerning our standards. They are openly available apart from the fact that normally we say you have to be an instructor or dive shop to buy them. We would certainly share them with other agencies if that was a desire. No problem at all. The question about can you learn initially on a rebreather? Yes. With PADI, not right now. Probably we will in the future. For the time being, we have decided it is more appropriate to start off on open-circuit and then cross over to closed-circuit. Checklists are a very good thing. I think they will be essential for technical diving long into the future. In recreational diving right now, in many cases it is the best we have. I see a potential alternative in the future because with machines becoming as intelligent as they are, there are alternative approaches. For example, we know that people can be lazy and distracted. They can make mistakes. An ideal scenario might be that a machine forces you to go through your checklist and does not allow you to dive as you would like unless you have gone through every step. Another approach is for the machine to do much of the checking for you. You need certain things to be checked, whether they are checked by a potentially unreliable person or a wholly reliable person is unclear. And this is not science fiction. Bill Stone showed us a video of a unit doing exactly that. We are not yet to the stage where a robot can take you diving, but we are going in that direction. I think that in addition to taking stock of the present status quo, we must consider what we would like to see happen in the future.

BLETSO: Flight training is based on a universal foundation of theory and then platform-specific training to achieve a type certification. Applying this to rebreathers, you may get your basic CCR certification on a simple unit, but the standard throughout the industry should be for intensive training on physics, physiology, and general rebreather construction and monitoring systems. Then going from one rebreather to another would require unit-specific training and necessary checkouts.

MESLEY: I think it is a fantastic idea about physiology training. And probably more important, it should be written by the people in the audience here whose job it is to understand and know advanced physiology, not by somebody who thinks he knows a lot about physiology.

I also have a comment about the amount of input that manufacturers have in instructor- and instructor-training programs because I, for one, being an instructor trainer, would absolutely relish having more input from the manufacturers. What we want to avoid is the dissemination of bad or unhelpful information that works its way down the levels. My last comment concerns how long can someone go without being in the water before a refresher is required? For me personally, when someone finishes a course, he needs to do as much diving as he can in a short period of time to secure the level of training he has received. In my opinion, people need help two or three or four months down the line, and they need retraining after six months.

TOM MOUNT: A lot of training agencies do not put standards on the Internet because their lawyers have told them to take them off. Regarding training initiation, I would start an 18-year-old son on a rebreather before open-circuit. These guys learn rebreather much more easily and may be more conscientious as they evolve.

One other thing to mention is that we did some testing on rebreather CO_2. We put divers in the water without scrubber canisters. The divers knew they were going to get a CO_2 hit. They were told to switch to OC the moment they felt unusual. The first thing that happens is confusion. So if you are confused, you make bad decisions. We tested a total of 100 people until the medical authorities told us not to do it anymore. Ninety out of 100 were brought up without bailing out. Most of them initially said, “I felt something unusual. Oh yeah, I did have some burning in my legs. I did have some shortness of breath.” What we have got to do in all of our training is emphasize confusion.

HEINERTH: I think the longest anyone ever made it in a pool test is 75 seconds, and most were blacking out at 45 seconds under high workload. [In the late 1990s, divers intentionally used a rebreather without a CO_2 scrubber in a swimming pool to see if symptoms could be detected and bailout effected.]

Just out of curiosity, a show of hands, how many people feel that even though this could make the legal issues more difficult, how many people would like to see all standards published on the Internet and publicly available? So that means you could be sued for not doing your job as an instructor. I would say that [show of hands] is the majority of the room.

MOUNT: Talk to the lawyers.

HEINERTH: We would still like to see that in our industry.

BARRY COLEMAN: Many of the issues raised today we [Rebreather Association of International Divers {RAID}] have actually considered. I am going to start with the issue of rebreather vs. open-circuit training to cover a few of the points. Our open-circuit courses all include information about rebreather diving, such as has the rebreather diver completed a checklist? Has he handed it to his buddy to confirm the checklist? Has that been handed to the manager or boat skipper? They are actually taught if they do not see this not to dive with their rebreather diver. On the rebreather side, a gentleman mentioned earlier the utility of having detailed information about rebreathers generally available. We put together a complete core level of education a few years ago and had a lot of information. How can we effectively get this to the students, and how can they actually learn this without having to go to a lecture? Because if the lecturer had to lecture all the information that you provide, you would be standing up there for about four days, and we all would have gone to sleep in the first hour. We thought about it, and we put it on the Internet. So it is a requirement that the student actually purchase the course. And by the way, when you register on the website, you can actually see our standards. Anybody who registered on the website can download our standards. And they have to actually read that information about rebreather diving. We even quiz them on things such as what skills they are going to do in open water, which is a good time to make a decision whether they want to take the step into practical training.

On the practical training side, we advocate teaching people to dive on rebreathers from the beginning because it instills a different mindset in the diver. As mentioned earlier, you put them on open-circuit, they get that mindset. So if we can instill the correct mindset from the beginning regarding checklists, safety, bubble checks, checking PO_2 on the way down, checking with buddies, PO_2 setpoints during the dive, confirming with the buddy what the setpoints are and actually acknowledging it, etc., we have an advantage over trying to change a mindset during training. Remember that the first impression can be the lasting impression.

The other thing we considered was the number of quality-assurance programs in the market today that are reactive to situations. So we asked how we can make quality assurance proactive instead. We have been able to make this work with the Internet. For example, we can tag any new instructor. And if that instructor is then appointed to teach a student, that tagging will come up immediately on our main computer system. This is worldwide. We actually had an incident recently where a guy was tagged. He was trained in Mexico and went to the Canaries. We tagged him. Before he even got in the water we had actually contacted the dive center in question, made sure he was doing everything right, and even contacted the student prior to him getting into the water. We stopped the course there and then. That is what we call proactive quality assurance.

HEINERTH: I am going to add an interesting thing about their program, specifically an independent, "Yes, I mastered this skill," check by the diver and, "Yes, he did actually master the skill" by the instructor. It is a two-way quality assurance, which is interesting.

BRIAN CARNEY: We follow a very similar process at Technical Diving International (TDI). Our standards are available for our members and facilities at any time electronically.

HEINERTH: And the public as well?

CARNEY: Not to the public, for very much the same reasons that Tom Mount alluded to. Bring it up with the legal people. One of the things I want to address is that we already work with other training organizations. Training departments talk to one another; it is our way of policing ourselves and policing the industry. This has been going on for quite some time. It is one of the reasons why it led to three of the technical organizations to get together and release our numbers at the last Diving Equipment and Marketing Association (DEMA) show. We have had sessions and communication over the year. We finally decided to share it so everybody can have that baseline. We have now opened lines of communication that I do not think would have existed without going through this process. Other organizations have already approached us about participating. We have already begun to set the basis for naming different type of DEMA conventions together. Basic certification is 30 m (100 ft), no decompression. Intermediate is lower, and advanced. Now we have some baseline for testing. Remember, diving is all recreational unless it is scientific, military or commercial. Finally, I want to address something about checklists. From TDI's perspective, instructors want to know what checklists to use. A central clearinghouse of all checklists from the manufacturers would be extremely helpful. We would definitely support an initiative with this goal.

Figure 2. CCR wreck diving. Photo courtesy Howard Ehrenburg.

JERRY WHATLEY: Regarding standards, the devil is in the detail, but as I have mentioned previously, the Rebreather Education and Safety Association (RESA) manufacturers have committed to publishing our training standards for our specific units. These will be absolute minimum standards. We look forward to training agencies exceeding these standards. I think we have got a lot of things started in the last year. I think that this meeting has really accelerated some of the initiatives. And I think that over the next year we are going to see changes in standards and the publishing of standards. When I hear talk of we are going to do this or we are not going to do that because of lawyers, that is not the job here. The job is to make this thing safe enough so that lawyers do not have work.

TYSALL: Rebreather manufacturers may want to talk to some of the surface-supply people regarding what they have done to eliminate product liability issues. Stringent manufacturers' checklists are used by our soldiers and our sailors.

WHATLEY: I think the main thrust of what we need to keep in mind, as Brian Carney stated, is that the diving that is not scientific, military or commercial is recreational. We need to keep that very clear, or we will be speaking with Occupational Safety and Health Administration (OSHA) and seeing the end of decompression diving for all of us. It is recreational. We need to keep it that way. We all know we need to improve. We are going to see some interesting times over the next year because we have a lot of detail work to get through, but we are extremely committed to getting through it.

PAUL RAYMAEKERS: We should publish minimum training standards so that everybody can see them before doing a course. If you go to the rEvo website, there is a complete description of the minimum requirements every student will have to meet. Regarding checklists, there is one thing that has not yet been highlighted. There is something of an art in making a good checklist. A checklist of 50 lines will never work. A very concentrated form that gives users a good feeling that they will dive in a safe way when they use it will make a difference.

HEINERTH: I would agree to a point. I would suggest, though, that the use of any checklist seems to be working because we are not finding the dead guys with checklists. So certainly things that are too onerous will not work for some, but it seems to me that people who are using checklists represent a certain type of diver.

INSTRUCTORS

HEINERTH: Who should supervise instructors? Right now we have training agencies certifying instructors, but we have manufacturers going, "Oh my goodness, what about that guy?" How can they work together better to either potentially revoke a credential or endorse a particular instructor? Should they be posting a list of endorsed instructors on their lists? And then the biggie, should instructors be required to prove currency when teaching an entry-level class? Should they be providing proof with logs for a particular rebreather that they are teaching on? How many rebreathers should they teach on? If they are certified in 12, are they current and capable to teach 12 at any given time? How many students should they teach every year, and should there be some sort of industry standard currency card? Should there be a Rebreather Pilot Association? I could present my Sentinel checklists to get a Rebreather Pilot Association endorsement sticker for the year to say that I am good on a Sentinel. But even though I have an Optima in my garage, I am not current on my Optima. So should there be something like that?

MICHAEL MENDUNO: We are talking about training standards, but there is another side, which is operational standards. When I was training in tech diving with Billy Dean, we had a set of SOPs. Rigging and plumbing, isolator valves, should you be off your diluent. Scrubber use, helium use, solo diving, gas switches, mouthpiece straps, limits. Is it worth it to develop a set of best practices not for training but for diving?

Second issue. When I first got my rebreather and was shopping for instructors, I asked what was needed and was told to bring a wetsuit. When I said I did not have one, I was told that it is much easier to do the training in a wetsuit. Ultimately, I did my course with Paul Haynes, who said I had to bring my drysuit. If I had learned in a wetsuit, I would have come back and had to figure out a lot of stuff on my own, maybe successfully, maybe not. Can it be said that if you are going to be diving dry, that is how you should do your course, period?

TYSALL: People call me up for classes. We are coming down to Florida. Where are you going to be diving? We are from Duluth. I tell them, "I should come up there to you and train in your backyard because that is what you are going to be diving. Taking you to Ginnie Springs or off West Palm Beach has its advantages, but it is not a realistic analog for what you are doing."

PAUL TOOMER: I want to make Scuba Schools International's (SSI) standpoint clear. We are just entering the rebreather market, so it is very exciting for us. For recreational rebreathers we have allowed a non-diver to enter into rebreathers, which is a hot topic. We think that with modern-day electronics and the format of the course, we have it buttoned down. But a couple of things that have come out of this meeting have been absolutely fantastic. We have looked at technical CCR. We have looked at the formats and listened to the other training agencies and tried to establish some sort of standardization between the courses within our own agency as well. We are thrilled with the response that we got from all the manufacturers to our requests for personalized checklists to go with our generic checklists. All the manufacturers have said they will help us build an individualized skill set that they would like done a specific way for their rebreathers — an important step since we are also seeing issues with this. Our standards are also easily accessible from the website. We have also decided to do much like what Kevin Gurr and Phil Short have done with the Sentinel: Each diver does a skill sign-off as they progress. We are going to do that as well with every rebreather, but we are also going to let the manufacturer have that sign-off sheet. We really are very keen on diver safety.

LOCK: We talked about automation. It has certainly improved aviation. But I have also found in aviation that automation has potentially gone a bit too far if teaching does not fully address the reversion moments. So the question of the agencies and the manufacturers should be how are you going to address training as more automation comes in, dealing with complex failures you cannot necessarily hope to solve straight off?

HEINERTH: I think that depends on recreational or technical as well, whether the response is simply bailout and surface.

LEON SCAMAHORN: One thing I did not see on your list of questions was how many times have you recently just gone diving, actually done the activity that they are teaching people how to do?

MESLEY: I have one question for the manufacturers. Would you like to have the power to revoke an instructor's certification if he is not following safe diving procedures?

SCAMAHORN: We already do.

MESLEY: Anybody not going to? All right. So that was an outstanding yes [that manufacturer's should be able to revoke an instructor's credentials].

HEINERTH: For those who do not know, Leon Scamahorn basically did a manufacturer's recall and required every instructor to come in for an update to make sure they are up to date with the most current operation and models out there. At the time [Innerspace Systems] "unblessed" many instructors.

ANDREW FOCK: We currently have a death rate of somewhere between five and ten times that of recreational divers. And while we have had a number of ideas before, we have no current evidence that any of us are here to make any difference in that death rate. We have a number of good ideas that have been put forward during the last few days on how to correct those things. We have no evidence that any of those ideas will make any difference to that death rate. Should we morally be suggesting that the recreational market adopt changes until we have our house in order?

UNIDENTIFIED SPEAKER: One thing I think we need to do culturally is encourage people to shop for the right instructors. There are a lot of instructors out there, some good and some less so. It needs to be brought to people's attention that they can go shopping for instructors instead of just taking whoever is closest or cheapest.

HEINERTH: How many people believe that we should have some sort of instructor currency requirement for teaching? And how many do not think so? I do not see any hands up in the room for not having a currency requirement for instructors. Let us put that in the record.

MOUNT: A couple of things. One, I would like to emphasize what Brian Carney said. There is a lot of communication between the agencies now, and instructors all have very strict quality-assurance programs. Second thing, we have had a checklist for about five years, but it does not check the manufacturer's checklist. It does the things the diver needs to do to go in the water. We require every instructor, every course, to use that. We have to have our own checklists.

TYSALL: You have heard us all talk about having to do this because of legalities. Everybody who is an instructor from open-water level and up, when you step outside your standards, you are done. How do we integrate manufacturers, training agencies and the legal reality that we live in?

CANEY: I want to address Andrew Fock's point. He was asking, "Is it reasonable to introduce rebreathers for recreational divers given what we know?" I would say yes, it is, but within certain parameters. And if you simply said, "Take whatever you have done in the past and do that in the recreational field," I would say, "No, that would be wrong." They need a specific program of training that is designed for the diver and a specific envelope in which to use it. There are two major components to this. One is restricting the envelope in which this is used, the recreational envelope, 40 m (130 ft) maximum depth, no overhead obstructions, etc. The second part is to limit the demands on the diver so they are reasonable for a recreational user. The approach PADI has taken is to define what we call the type R rebreather, which is a machine that is relatively simple to use, a sophisticated machine but one with a quite easy human-machine interface. With those two components combined with an instructor system approach, which is delivering all the critical information a student needs, we feel it is quite reasonable and are about to introduce this into the recreational world.

TYSALL: It sounds like SSI and PADI are kind of in line.

UNIDENTIFIED SPEAKER: I would like to address the topic of new divers starting on CCR. I believe, first of all, that a comprehensive course in rebreather principles and physiology would be an acceptable barrier for entry so you cut out the bottom percentage that should not be diving rebreather at all. In addition to this, what I think is important, one training methodology does not necessarily fit all. I do not think that it is appropriate for most divers to begin on CCR. However, such individuals probably do exist, and they can learn to dive safely on CCR at the same time as on open-circuit. They should probably have to ask for that course, but if they are forced into another training mode, the risk is that they rush their open-circuit training, and they do not learn the basic skills that they should. I believe that such individuals could probably be able to dive safely on CCR to begin with if they were taught open-circuit along with that so they did not feel they were missing out on what they really wanted.

HEINERTH: Recently I did an eight-hour workshop. It was a class with people who did not own rebreathers, and it was called "Rebreather 101," physics, physiology, basic operations, and how they work. It was CE testing and what it means, how you choose a rebreather without endorsing any one particular rebreather. How to weigh your pros, cons, risks, management and budget to make a good choice. People seemed to really enjoy it. They felt that it gave them the better tools to make a choice on finding an instructor. I would encourage the agencies to consider breaking that away and offering a certification level from which divers can move on to a full rebreather class.

TYSALL: If you are becoming a naval aviator, you go through basic training and then training for a specific airframe. The Army requires everybody to go through rotary wing first and then you can go to fixed wing training.

JEFF BOZANIC: I am going to talk on two issues. The first is currency. I am certainly not against it, but I am against the way it might be defined. Is currency 12 dives a month, 12 divers a year, 12 dives a decade or 12 dives a century? Those are all very different. The second part of currency deals with how much background experience the person has. Currency for somebody who has done one class with one student is very different from currency for somebody who has done 500 students over the period of a few years. It is no different than somebody who learns to open-circuit dive and does not go diving for a year versus somebody who has done 500 dives and takes a year off. The latter individual can generally return with no problems whatsoever.

The second thing I want to address is the concept of teaching people who have never been diving before on rebreather. I personally have no problems with it. I have taught three students with no open-circuit diving experience whatsoever. One did fine, one needed a bit of extra time, and one I did not certify. That is not too dissimilar from what I would have expected to have seen if they started on open-circuit first. The difference is that the open-circuit classes typically have to be longer than they are now because you have to cover enough open-circuit skills to provide them the ability to go to backup or to bail out and get to the surface. You also need to increase the class time and duration to include all the other factors they need, for example, knowledge of waves and surf and hydros and all those types of things.

ELAINE FERRITTO: There is quite a bit of experience in this room. The majority of folks who have traveled here have years upon years upon decades of diving. I am one of the lucky few who did my four open-circuit dives and went straight to rebreathers. And as a current instructor for the Titan rebreather, I will say that when you first teach someone, there is a lot of information to absorb. Some students learn it with no problem, others need more time. I would love to see training standards and more information available online as resources where people can look back. You have to look at future generations for which visual learning is important. Books and training materials must be stimulating. Addressing future generations requires more resources so that after the class, when the instructor's words are not quite as clear any more, people can refer back. I do not know who it comes down to. Is it the manufacturer who is responsible for putting that information online? Other divers? Training agencies? Is it somewhere that a certified student can sign into the website and say, "Hey, I forgot how to do this." Instead of eliminating that kind of experience, I would like to see more accessible online resources.

RICHARD HARRIS: To paraphrase Andrew Fock, should we be encouraging this technology for newcomers to diving or to the recreational market before we put our house in order? My interest is in risk and accidents. I am not an instructor and have no experience in that area. It will be for the training agencies to decide whether it is worth the time and effort for their business model. But Mark Caney made the point that this will be confined to the first 40 m (130 ft) of water. The units will be specific for that group and made in such a way as to have single responses to problems that arise. But it is important to remember that while we understand that the higher-risk dives can be the deeper dives, we also have a lot of divers dying on the surface or in very shallow water from human-error problems. These risks may be similar between groups and maybe still higher in a less experienced group. So I still would promote an attitude of caution.

RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

A TRIPARTISAN LOOK AT THE STATE OF REBREATHERS: ANDI, IANTD, TDI COLLECTIVE REBREATHER CERTIFICATION NUMBERS AND MARKET ANALYSIS

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ABSTRACT

American Nitrox Divers Inc. (ANDI), International Association of Nitrox and Technical Divers (IANTD) and Technical Diving International (TDI) have combined their more than 65 years of collective rebreather training experience into a summary of closed-circuit rebreather (CCR) and semiclosed rebreather (SCR) certifications issued from 1990 to 2011. This represents more than 30,000 divers who were certified on 27 types of rebreather. Certifications were identified as basic, intermediate, or advanced and as CCR or SCR. Total annual certifications increased at a rate of about 200 per year, reaching 2,600 by 2011. A four-year forecast estimated that annual certifications will grow by about 160 per year, reaching nearly 2,800 in 2015.

Keywords: CCR, closed-circuit, diver training, SCR, semiclosed-circuit, training

INTRODUCTION

The three largest rebreather certification agencies came together to understand the opportunities with respect to rebreathers and foster openness as well as discuss their individual responsibilities as industry leaders in the diving community. The need for knowledge of precise rebreather certifications numbers is overdue. This paper will summarize rebreather certification numbers and analyze their trend as well as estimate the future of rebreather certifications.

METHODS

The geographical distribution represents certifications from the entire world. American Nitrox Divers Inc. (ANDI), International Association of Nitrox and Technical Divers (IANTD) and Technical Diving International (TDI) have rebreather instructors in every part of the world. Primary in our minds was the validity of the data. As seems evident, there may be cross certifications between agencies. That is to say, some divers may seek certifications in two or more certification agencies, which would affect the resulting certification agency's numbers. To alleviate this, our respective agencies opened our certification files to one another. We traded all unit-specific certification data on rebreather training. We combined our numbers and confirmed the accuracy of the data for a period of three non-sequential years and cross-checked each person by name who was certified in a geographical area, by year, unit and level of training. This process allowed each agency to personally verify numbers of certifications. The data mining allowed us to determine a 1 percent duplication effort. We then applied that duplication decrement number (γ) across all the 22 years of numerical data. All data presented represented the γ-reduced data. The data represented herein includes a correction for duplication of data. A single diver may be represented as having obtained certifications on different types of rebreathers or at different certification levels, therefore his or her name may appear twice in the data, but any duplications for the same certification level on the same rebreather was removed.

The resultant data was analyzed for the mean by summing the total number of certifications and dividing by the number of years, yielding the mean over the spread of years. Since the early years of rebreather certifications were very low and manufacturers were not regularly producing rebreathers, the 69 divers certified between 1990 and 1995 were not counted when calculating the mean. The mean was calculated using the sum of the numbers divided by the amount sampled.

Standard deviation shows how much variation or "dispersion" exists from the mean value. A high standard deviation indicates that the data points are spread out over a large range of values.

Our three companies have slightly different methods for classifying rebreather certifications. Basic includes any entry-level program to closed-circuit rebreathers (CCRs) and semiclosed rebreather (SCRs) as well as no-stop diving and depths not greater than 100 ft (30 m). Intermediate qualification comprises any training with minimal decompression. Advanced qualifications include dives that generate both hard and soft ceilings that are significant in nature such as trimix, cave and exploratory qualifications.

Since forecasting the market data was an important consideration, we turned to the Holt analysis. Holt's linear exponential smoothing captures information about recent trend and time series data that is non-seasonal. For any statistical test, the probability of making a Type I error is denoted by the Greek letter alpha (α), and the probability of making a Type II error is denoted by Greek letter beta (β). Type I errors, also known as false positives, occur when you see things that are not there. Type II errors, or false negatives, occur when you do not see things that are there. Alpha (α) was chosen to be 0.3, and beta (β) was chosen to be 0.03. The equations are:

$$L_t = \alpha Y_t + (1-\alpha)(L_{t-1} + b_{t-1})$$
$$B_t = \beta(Lt - L_{t-1}) + (1-\beta)b_{t-1}$$
$$F_{t+m} = L_t + b_t$$

Lt and bt are respectively (exponentially smoothed) estimates of the level and linear trend of the series at time t, while Ft+m is the linear forecast from t forward. The group understands the Holt analysis continues to have less validity each year after projections are incorporated to determine another year of trend data. That is why the forecast was stopped after four years.

RESULTS

Table 1 shows the total annual rebreather certifications by ANDI, IANTD, and TDI from 1990 to 2011 with the number of basic, intermediate, and advanced certifications and the number of SCR and CCR certifications. These data indicate that more than 30,000 divers have been certified on 27 different types of rebreathers at varying levels from 1990 to the present.

Figure 1 shows total annual certifications as well as CCR and SCR certifications. The mean certifications per year was 1,852 divers (number based only on 1996-present) with a standard deviation of 707. Further study of the data reveals that greater than 66 percent of the years studied reflected a number at or greater than the mean, which indicates the market is continually growing and has significant recent growth. A growing trend of CCR certifications was noted. Annual certifications were greater than the mean from 2001 forward. SCR certifications peaked in 2001 and trended downward thereafter until a small increase in 2011.

As demonstrated in Figure 2, basic rebreather certifications (new rebreather divers) total almost 18,000 divers. We estimate this is about 80-90 percent of the total rebreather divers who were certified worldwide. More than 12,000 divers carried on to continuing-education classes on rebreathers (50 percent at the intermediate level and 50 percent at the advanced level). New rebreather divers are at almost an all-time high in the market, save a single year in 2001.

In Holt forecasting, an alpha parameter smaller than 0.40 is often used. An alpha of 0.3 was chosen because it has the smallest mean absolute error (MA Error). Figure 3 shows the Holt analysis projections depicted and suggests certifications by ANDI, IANTD, and TDI will increase from 2,600 in 2011 to 2,900 in 2015, although growth could be under- or overestimated by 240-300 certifications per year based upon the assumed MA errors. The raw data used for all calculations depicts the duplicate certifications removed and is contained in Table 1.

CONCLUSIONS

Rebreathers are a growth market. Basic rebreather certifications are the highest they have been and continue to increase. CCR certifications continue to grow, but we have noticed a minor resurgence of SCR certifications in the last two years.

Table 1. Total rebreather certifications from 1990-2011 by ANDI, IANTD, and TDI after removing an estimate of multiple diver listings.

Year	total	SCR #	CCR #	Bas	Int	Adv	Year	total	SCR #	CCR #	Bas	Int	Adv
1990	10	5	5	8	2	0	2001	1935	1140	795	1516	193	227
1991	2	1	1	1	1	0	2002	1939	917	1023	1312	254	373
1992	5	2	3	2	0	3	2003	1959	613	1346	1210	329	421
1993	10	0	10	6	4	0	2004	2335	523	1813	1271	442	623
1994	6	0	6	2	3	1	2005	2303	426	1877	1287	518	501
1995	36	27	9	29	4	3	2006	2336	347	1990	1233	422	682
1996	460	381	79	386	16	58	2007	2470	239	2231	1278	586	606
1997	978	827	151	835	17	127	2008	2189	106	2083	1152	294	743
1998	1020	717	303	895	27	98	2009	2181	140	2041	944	549	662
1999	1024	653	370	844	53	123	2010	2818	72	2745	1338	742	738
2000	1066	454	612	722	147	198	2011	2616	214	2402	1408	573	635

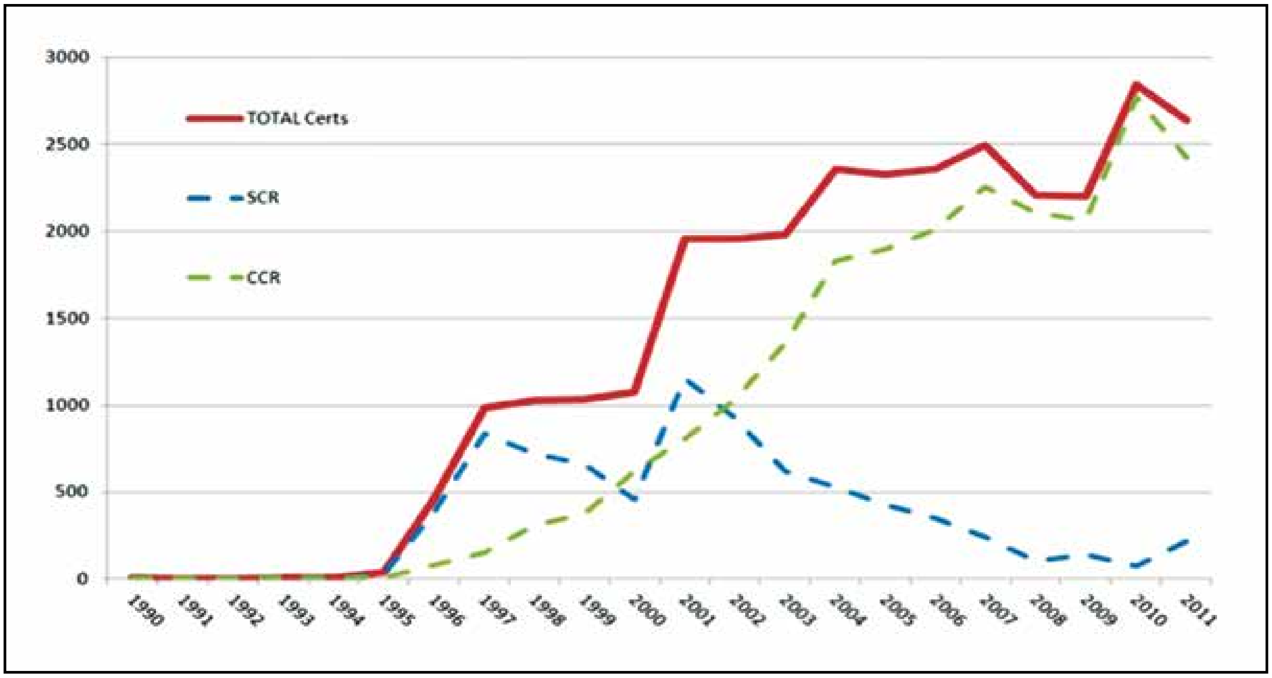

Figure 1. Total annual rebreather certifications and SCR and CCR certifications.

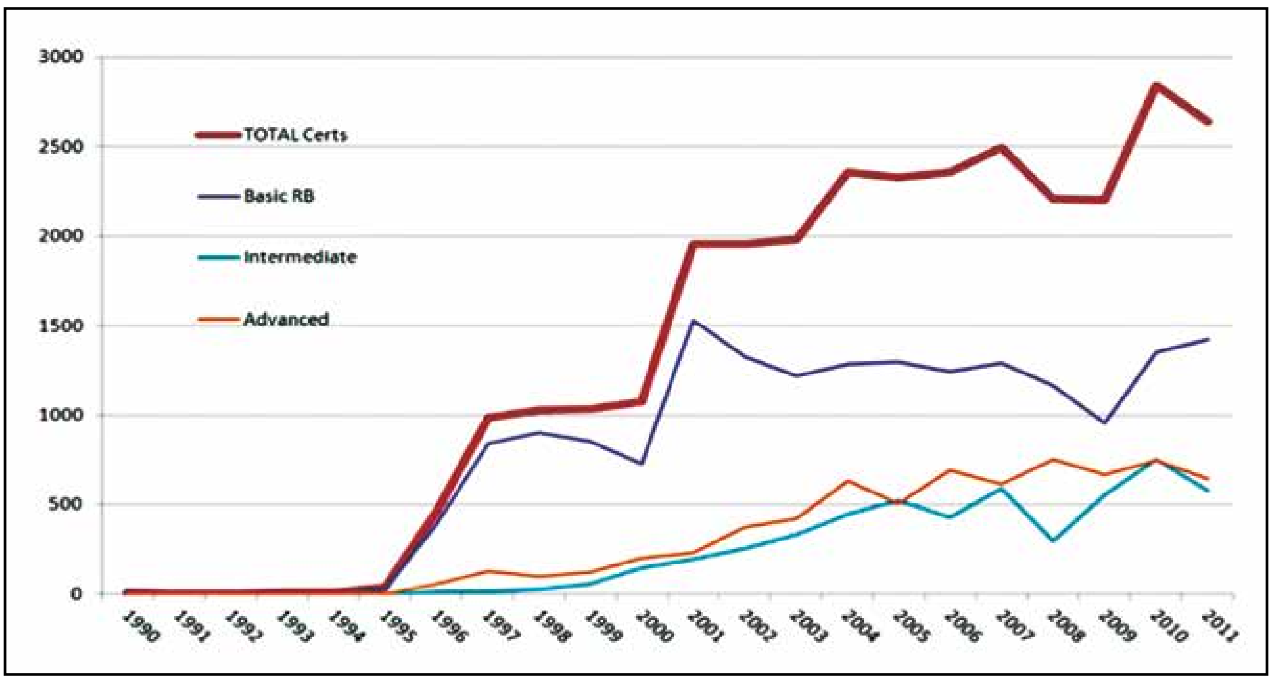

Figure 2. Analysis of skill levels of rebreather divers.

ANDI, IANTD and TDI are three different training agencies. We have similarities and differences in the conduct of our individual businesses. Together we have a successful training methodology with 65 years of experience. We thoroughly enjoyed working together, and we will continue to work together in the future to foster openness as well as discuss our individual responsibilities as industry leaders in the diving community. While we may have minor differences as competitors, we agree on a few training items. The most important of which is that the rebreather instructor's experience matters when choosing an instructor.

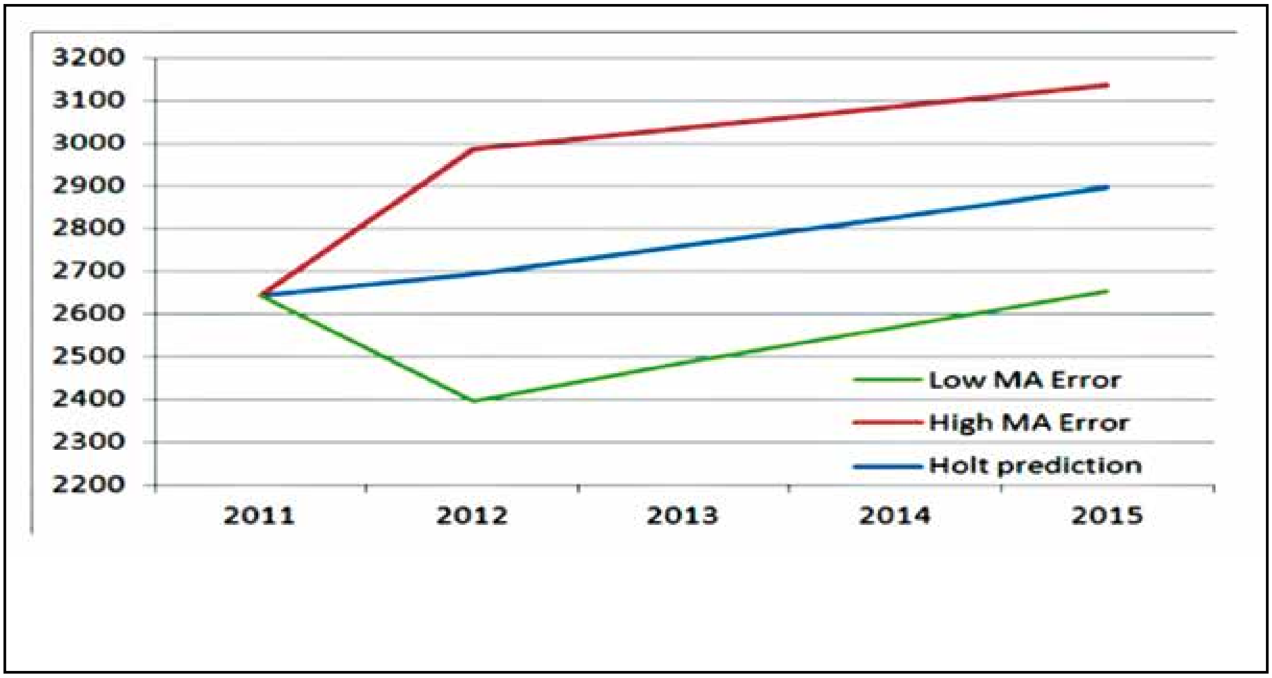

Figure 3. Holt Analysis projections with alpha = 0.3 and beta = 0.03.

REFERENCE

Hyndman RJ. *Forecasting with exponential smoothing: the state space approach*. Springer Press: Berlin, Germany; 2008; pp. 14-15.

PUBLIC DISCUSSION

JOSEPH DITURI: Trust is a bucket filled with an eye dropper. When we all got together, we started dropping little drops in this bucket. It took a long time for us to go, OK, I am going to share my data with you. We have known these guys for 20 years, and people who do not think that we all talk together, they are wrong. Ed is on speed dial, so is Sean, and so is Brian. The bigger focus is we are competitors, but we are not our enemies. Our enemy is skiing, snowmobiling, any other sport. But regardless, we all agree that experience matters when picking an instructor. It was echoed this morning in the video that was played in the main hall, and what that gentleman said right off the bat was experience matters. It is agency independent. If you get a good instructor out there, you will get good, adequate training.

ED BETTS: The information we presented represents international numbers. I think it was more than 25 countries.

RANDY THORNTON: I am curious how this growth projection equates to the dive industry's general growth or decline.

BRIAN CARNEY: If we draw a direct comparison to our numbers with the DEMA certification census, there is a slight decline in total open-water people coming in the U.S. for PADI, SSI and ourselves. CCR is seeing growth over total number of people coming into the sport, which is flat at this point.

JAMES ROBERTSON: I would just like to applaud the three of you gentlemen for doing this, because there is quite a lot of bravery in showing numbers up when no one else is doing so. I think it is hugely important for the entire industry that we are all far more open and transparent. You guys have taken a very important step forward.

JERRY WHATLEY: I would also like to applaud your effort. The communication and the data has been very valuable. One of our biggest concerns is more data. The question I have for you folks is you mentioned in your methodology that you compared certifications. Do you have a metric for the last five years, if you average 1,800 total certifications a year, are those unique individuals, or is this a subset getting multiple certifications on different units and not rebreathers?

DITURI: 1,852 was the total number of beginner certifications. The advanced certifications totaled almost that number. That's about 3,000 people total. There are minor duplications in that one person may train on several rebreathers. We did not break out that inconsistency, but we traded names, units, and experience levels to look for people who got certs from TDI, INTD and ANDI. We found 1 percent multiple certifications. So it is 1 percent duplication.

WHATLEY: Has continuing education affected those who are staying with the sport?

BETTS: Much more so, Jerry, than as an entry-level program. We have a 50 percent advance to intermediate and a 50 percent advance to exploration. A given diver is definitely averaging two or three certifications.

STEVE LEWIS: There seems to be somewhere between a 50 percent and 66 percent retention rate. How does that compare with open-circuit divers?

BETTS: As somebody who operated multiple dive stores for more than 25 years, I only wish that I had 50 percent of the people that I trained last year diving with me this year. In rebreathers, you can see it.

CARNEY: Steve, it is speculation at this point, and we would be lying if all of us were not saying it was speculation. And the reason it is speculation is none of the training agencies share that data. So if we want to share the data, let us share the data.

GARRETH LOCK: You are showing that the market is expanding, which means you are going to need to expand your instructor base. How do you plan to ensure that the standards are maintained among those instructors? One of the things that came out from the UK study was that manufacturers and agencies do as much as they can to ensure rebreather safety, but instructor standards are falling down.

CARNEY: Our three companies have made a decision not to reduce our standards, and in some cases we will be increasing our standards collectively. That was a determination when we started comparing data. We are not enemies. Instructors who violate the standards will be put on probation, and that information will be shared among the three agencies. Instructors like that are the problem, not the agencies and not the manufacturers.

DITURI: We have agreed unanimously not to reduce the training standards for instructors. A trend in the industry is to say less training is more. We have to talk about and face the 800-lb gorilla. It will be almost criminal to reduce our standards. To police the instructors, all of us have instructor updates that require a minimum amount of time on units and a minimum amount of dive time.

DAVE BURROUGHS: You said you looked at both domestic and international numbers. Did you break it out in sampling that you can share with us or will share with us?

CARNEY: At this point, no. We thought it was important to do the global numbers so that everyone can get an idea just how big the sport is.

BETTS: Even one fatality is one too many. But what is the problem? Until we can identify the problem, there should be no backing down on instructor standards, instructor policing, training standards, performance standards, criteria standards, refreshers and competency levels. That is a unified statement from the three of us.

TOM MOUNT: We know open-water divers have a heavy washout. But rebreather divers seem to take many courses and make many dives. Even in training there are more dives in a rebreather course than in an open-circuit course. We need an estimate of how many dives people do. This would give us a denominator we could use to measure safety.

BETTS: Regarding diver retention, ANDI has many divers who have done two or three courses on different units. I did not buy a unit yet. One diver got nine certifications. That's extreme, of course, but many of these divers stay with it and keep training.

DR. RICHARD VANN: What fraction of all the rebreather training would you estimate has been done by your three agencies, and what fraction has be done by other agencies or instructors?

DITURI: We discussed mentioning this but did not as it would just be speculation. Having said that, Joe Dituri's speculation is 85 or 90 percent.

CARNEY: I concur.

BETTS: In regions where ANDI is strong, we have more than 90 percent. I am confident in the 85 to 90 percent estimate.

CARNEY: Would all the ANDI, IANTD, and TDI rebreather instructors in the room raise their hands. Would all those rebreather instructors who do not hold a rating with one of our three organizations put your hand up. This informal count suggests it is more than 90 percent.

DITURI: We would welcome other training organizations to share their numbers with us. Openness would be good for the community.

PAUL HAYNES: Is the goal of your three organizations to harmonize your standards?

CARNEY: Yes, we did that by defining basic, intermediate, and advanced. Perhaps this will help us to figure out why incidents happen, and that might lead to further standardization. If we found, for example, that increasing the number of hours to become an instructor reduced incidents, we would all do so.

HAYNES: After 20 years of competition, this is very positive. Excellent.

DITURI: We may be on the verge of establishing a technical scuba training council.

BURROUGHS: How is this information going to be made available to rebreather manufacturers?

BETTS: The information is available right now in this handout and will be published in the RF3 proceedings. We will also post it electronically.

BURROUGHS: You suggested that your three agencies will collectively investigate potential fatalities and accidents to look for evidence that standards should be modified. How will you communicate that information to the manufacturers of rebreathers?

CARNEY: We are working with RESA to do just that. But it cannot just be the training organizations. This is a combined effort with manufacturers, training agencies, Divers Alert Network, and others. We will disseminate the information once we have it in hand, but we need help to get there.

BURROUGHS: Do you need to be a member of RESA to get the information?

CARNEY: I do not know the RESA membership requirements. A group of manufacturers willing to work collectively is important. We hope the training agencies can do the same.

WHATLEY: RESA is a group of manufacturers and training agencies, and we are looking for more. RESA is intended to help both groups work together to improve safety in the industry and effect a positive culture change. We are trying to make progress collectively. Nobody can do it alone. I will give a talk about RESA later today.

VANN: The history of this training session goes back to the 2010 fatality workshop held by DAN in Durham. Drew Richardson made a revealing presentation of 40 years of PADI fatality data. Brian Carney was there, and during planning for Rebreather Forum 3 he suggested that the technical training agencies might cooperate in summarizing their training data. Brian made it happen, and it's a good start. I am really pleased that Brian brought it up, and he, Joe, and Ed were willing to work together. It was a fun process, was it not, guys?

CARNEY: I have got a little less hair as a result. Notice I am sitting between them.

BETTS: It took a little bit of courage to share your business data. Joe was correct in describing the process as filling the bucket of trust one drop at a time. "OK, here's all the rebreather certifications I did in this country on these units with these people, and here are the names." It was a lot of information to share and took a little bit of effort.

CARNEY: TDI was the new guy to the group, and I cannot give enough kudos to Ed and Tom. They had many years of history, and their willingness to open up and work as a group testifies to where they want this sport to go. I am really happy to work with them.

HMS Hermes*, Sri Lanka. Photo by Andrew Fock.*

REBREATHER FORUM 3 CONSENSUS

Simon J. Mitchell
Auckland, New Zealand
Session Moderator

Editors' note: The Final Consensus Statements are given below. The discussion that led to the consensus appears after the Consensus Statements. The discussion was excerpted from a transcript of the meeting provided by a court reporter. Editorial changes were made to correct grammar and remove extraneous comments. Every effort was made to retain the spirit and intent of the original discussion.

FINAL CONSENSUS STATEMENTS

CHECKLISTS

The forum acknowledged the overwhelming evidence demonstrating the efficacy of checklists in preventing errors in parallel fields that share similar technical complexity. Two recommendations regarding checklists were consequently agreed:

Checklists 1. The forum recommends that rebreather manufacturers produce carefully designed checklists, which may be written and/or electronic, for use in the predive preparation (unit assembly and immediate predive) and postdive management of their rebreathers.

- Written checklists should be provided in a weatherproof or waterproof form.
- The current version of these checklists annotated with the most recent revision date should be published on the manufacturer's website

Checklists 2. The forum recommends that training agencies and their instructors embrace the crucial leadership role in fostering a safety culture in which the use of checklists by rebreather divers becomes second nature.

TRAINING AND OPERATIONS

Training and Operations 1. The forum applauds and endorses the release of pooled data describing numbers of rebreather certifications by training agencies and encourages other agencies to join American Nitrox Divers International (ANDI), International Association of Nitrox and Technical Divers (IANTD), and Technical Diving International (TDI) in this initiative

Training and Operations 2. The forum endorses the concept of making minimum rebreather training standards available in the public arena.

Training and Operations 3. The forum endorses the concept of a currency requirement for rebreather instructors. We recommend that training agencies give consideration to currency standards in respect of diving activity, class numbers, and unit specificity for their instructors.

Training and Operations 4. The forum recognizes and endorses the industry and training agency initiative to characterize "recreational" and "technical" streams of sport rebreather diver training. These groups will have different operational, training and equipment needs.

ACCIDENT INVESTIGATION

Accident Investigation 1. The forum recommends that training agencies provide rebreather divers with a simple list of instructions that will mitigate common errors in evidence preservation after a serious incident or rebreather fatality.

- These instructions will be developed under the auspices of the Undersea and Hyperbaric Medical Society (UHMS) Diving Committee in consultation with the relevant RF3 presenters.

Accident Investigation 2. The forum endorses the concept of a widely notified centralized "on-call" consultation service to help investigators in avoiding errors or omissions in the early stages of a rebreather accident investigation and to facilitate referral to expert investigative services.

Accident Investigation 3. The forum recommends that in investigating a rebreather fatality the principal accident investigator invite the manufacturer of the incident rebreather (or other relevant equipment) to assist with its evaluation (including the crucial task of data download) as early as is practicable.

Accident Investigation 4. The forum endorses the Divers Alert Network (DAN) worldwide initiative to provide a means of online incident reporting with subsequent analysis and publication of incident root causes.

DESIGN AND TESTING

Design and Testing 1. The forum recommends that all rebreathers incorporate data-logging systems that record functional parameters relevant to the particular unit and dive data and that allow download of these data. Diagnostic reconstruction of dives with as many relevant parameters as possible is the goal of this initiative. An ideal goal would be to incorporate redundancy in data-logging systems and, as much as practical, to standardize the data to be collected.

Design and Testing 2. The forum endorses the need for third-party premarket testing to establish that rebreathers are fit for purpose. Results of a uniform suite of practically important unmanned testing parameters such as canister duration and work of breathing (qualified by clear statements of experimental parameters) should be reported publicly. Ideally, this testing should be to an internationally recognized standard.

Design and Testing 3. The forum acknowledges recent survey data indicating a poor understanding of rebreather operational limits in relation to depth and carbon-dioxide scrubber duration among trained users and therefore recommends:

- training organizations emphasize these parameters in training courses
- manufacturers display these parameters in places of prominence in device documentation and on websites

Design and Testing 4. The forum strongly endorses industry initiatives to improve oxygen measurement technologies and advocates consideration of potentially beneficial emerging strategies such as dynamic validation of cell readings and alternatives to galvanic fuel cells.

Design and Testing 5. The forum identifies as a research question the issue of whether a mouthpiece-retaining strap would provide protection of the airway in an unconscious rebreather diver.

Design and Testing 6. The forum identifies as a research question the efficacy of a full-face masks for use with sport rebreathers.

DISCUSSION

SIMON MITCHELL: This is a session in which we are going to try to pull together a lot of the things that have happened over the last three days. Neal Pollock mentioned that several of us have been keeping an eye on what has been going on to put together a series of statements that we can debate this afternoon. We are identifying some pragmatically useful points on which it might be possible to reach a consensus. A lot of this information will appear in the papers that individual authors will provide, but this is where we take ownership of it as a forum. You might think that some of these things are a statement of the obvious, but remember that many of the people who read these proceedings were not here. You must also remember that we have not captured all the key points raised in the meeting. Much of what was discussed cannot be distilled into simple statements. If we have time at the end, we can open the floor for any new points.

I have predrafted a series of statements, which we will open for discussion. It is much easier to get discussion going and reach consensus if you start with something to argue about. If you raise a point that suggests that one of these statements needs to be modified, it will be changed in real time as we proceed. I ask you to avoid anecdotes that prove the exception to a particular point if that point is overwhelmingly supported otherwise. This is a very imprecise science. There is always a story that proves the exception to a rule. Those stories are not particularly useful if it is clear that we are going in the right direction.

We will reach a consensus by simple show of hands and visible majority. If it is close enough for a count to be required, we will say there is no consensus. This is a very pragmatic approach.

This is our first draft statement: "The forum recommends that rebreather manufacturers produce carefully designed checklists that may be written and/or electronic for use in the predive preparation and postdive management of their rebreathers. Written checklists should be provided in a weather- or waterproof form."

There are a few elements of that statement that speak to some of the points that were made in the recent session. I think it was Gavin Anthony who pointed out that they have to be weather- and/or waterproof. I think it was Mark who pointed out that we are getting sophisticated in the way these devices can run these checklists for us. We already know there are rebreathers with electronic checklists. Some of them are forced checklists. So this embraces all of those. And it does not give any extra weight to either one at this stage, which is probably appropriate. We do not have evidence pointing to efficacy of one over the other. We are going to come back to encouraging checklists and creating a culture for them in the next statement. Is there anybody who would like to speak to this statement?

JILL HEINERTH: Could I ask you to add that these be published on the Internet and marked with a date revision so that we are clear as to when they are current?

MITCHELL: We will wordsmith to add that later. Anything else?

KEN SWAIN: I would amend predive preparation into two parts. Rather than predive preparation, say unit assembly and immediate predive. Break it down into two parts. One putting the unit together, and the other just before you roll in the water.

UNIDENTIFIED SPEAKER: Agreed.

JOSH THORNTON: As far as publishing them on the Internet, while sitting in this meeting I got on GoDaddy and purchased all versions of rebreather or CCR checklists domestic. Whether we put it together or turn it over to someone else, we encourage the manufacturers to put information up on our website.

MITCHELL: Thank you. Is there anybody who disagrees with this statement? For the record, that statement is unanimously passed.

The second statement speaks to the issue of creating a safety and checklist culture: "The forum acknowledges the overwhelming evidence demonstrating the efficacy of checklists in preventing errors in medicine. We, therefore, recommend that training agencies and their instructors embrace the crucial leadership role in fostering a positive safety culture in which the use of checklists by rebreather divers is emphasized."

I have not gone into details about how training agencies should do this. We could spend a lot of time talking about that. I also think that we should trust the training agencies to be sensible and understand the key role that they have. I am not sure that we need to be more specific. Let us open it up for discussion.

TOM MOUNT: We have a checklist called a presafety drill check that is not unit-specific. It covers the things that must be done in the water within 15 minutes.

MITCHELL: Thank you. Are there any comments around this particular issue about training agencies taking a leadership role in promoting a checklist culture?

DALE BLETSO: I would only state that instead of saying "emphasize," it "becomes second nature." It actually becomes a cultural thing. They do not think about it. It is just done. Emphasize means you are kind of encouraging people to do it. It has to be part of the whole culture where it becomes second nature.

MITCHELL: I do not have a problem with strengthening it to "becomes second nature." I think that is what we are trying to imply by culture.

TONY HOWARD: I think we need to promote consistency and coordination across the industry so training agencies are not promoting unnecessarily different formats, and all meet a minimum standard of what should be in the checklist.

MITCHELL: I do not have a problem with the concept, but each rebreather is different in subtle ways. If I was a rebreather manufacturer, what I would say to you is, "Leave it to me to create the checklist for my rebreather, and I will do a good job of that." I do not want to have to try to match what I am doing exactly with what the manufacturer down the road is doing.

HOWARD: I completely agree. That is where it has to be coordinated with the manufacturers. Many agencies will train on the same rebreather. We should have a consistent approach on the way each rebreather is trained for. The individual user may not know that the other agencies are dealing with it differently or the same. As an industry we should be consistent. The consistent approach should be apparent in future audits.

MITCHELL: How would you alter the wording to that?

HOWARD: That is a damn good question.

Figure 1. Buoyancy control and self-rescue are important CCR skills to be mastered. Photo courtesy Richie Kohler.

NEAL POLLOCK: Simon, the first sentence makes me uncomfortable. The focus of this meeting was not medicine. I believe you should take out the reference to medicine.

MITCHELL: I am happy to take it out. The reason I put it there is because we had a representative of the educational profession telling us that to drive change you need an evidence base. We do not have that in diving. How many people in the audience would object to me taking the reference to the medicine out?

GARETH LOCK: Just to change it to say "preventing errors in medicine."

MITCHELL: What about "preventing errors in parallel fields"?

POLLOCK: The latter works.

MITCHELL: Everyone happy with that? Is there anyone who wants to speak to this statement?

UNIDENTIFIED SPEAKER: I think it should be the manufacturers' checklist to make it clear that you are not dealing with lots of different checklists. I think "second nature" should be replaced with "mandatory."

MITCHELL: "Mandatory" is a strong word. How many people here would be happy with "mandatory"? I am one. How many people would be unhappy with "mandatory"?

UNIDENTIFIED SPEAKER: How do we make it mandatory?

MITCHELL: That is not the issue. It is a culture. We cannot make anything mandatory.

RICHARD WALKER: "Mandatory" does have a legal implication you may not wish to introduce.

MITCHELL: How many people are happy to leave it as it is? How many people insist that we change it? We will leave it as it is. What was the other suggestion? They are going to be manufacturers' checklists, are they not?

GAVIN ANTHONY: One of the recommendations is the manufacturers produce checklists. A lot of training agencies have their own way of presenting training information. If you define this as a manufacturer's checklist, it may not fit in with the training way of presenting.

MITCHELL: I take that point and tend to agree with it.

LEON SCAMMERHORN: I think there is room for both philosophies. Generally, aircraft manufacturers produce procedures manuals and checklists for the aircraft. The operators in an air carrier environment then produce operational checklists based on the manufacturers' form so that there is not a conflict. They can go further. Training agencies are primarily interested in the procedures, not the building of the unit. I would say that for a general statement perhaps the use of manufacturers' checklists in coordination with the training agencies' procedures. But the manufacturers cannot release the concept of specifying the limitations of the unit and the correct assembly and pretests of the unit.

MITCHELL: Why do we not take this out?

JEFF BOZANIC: We do not want to make any text so specific, tying it to a manufacturer, training agency or anything else, such that we stifle information.

MITCHELL: I think the intent of the statement is pretty clear and unambiguous. Time for a vote. Is there anybody who objects to this statement as it is currently written? For the record, we have a unanimously accepted statement.

The third statement was generated during the last discussion: "The forum endorses the concept of making minimum rebreather training standards available in the public arena." This does not disavow the concerns about legal implications. It is just saying what we would like to see.

POLLOCK: Can it just be "recommendations" rather than the wordier "endorses the concept of"?

MITCHELL: It is wordy. I think if I put "recommendations" in here, I am going to have a bunch of unhappy people. If I leave it as it is, is there anybody who would object to it? If I change it to "recommendation," is there anybody who would object to it? There are a few. So I am going to leave it wordy. Is there anybody who objects to this statement? Good. That goes on the record as a unanimously accepted statement.

Number 4: "The forum unanimously endorses the concept of a currency requirement for rebreather instructors." I used "unanimously" since Jill Heinerth already took that vote. Then it was Jeff Bozanic who said there are concerns. So the forum recommends, not mandates, that training agencies give consideration to currency standards in respect to diving activity, student numbers and unit specificity for their instructors. In other words, we are giving guidance to the way we think they should think, the things they should think about, but we are not saying they have to do anything. Jeff, you were the one who raised that concern. Do you want to say anything?

BOZANIC: Other than the fact that this is a very self-selected group that is probably much more active than the average recreational dive instructor, we must not lose sight of the fact that we have to keep the entire industry in mind and the applicability of what is going on.

MITCHELL: And we are leaving it entirely open for the training agencies to do that in a sensible way.

MOUNT: The only thing is student numbers and class numbers.

MITCHELL: Is there anybody who disagrees with this statement as it is currently written? Good. That goes down as unanimous agreement.

Now, a little bit of background for the next three statements. We are going back to the discussion of accident investigation. A lot of this comes from David Concannon's presentation. I think we all agree that inadequate accident investigation and the consequent lack of accurate data was a recurring theme. And to me and the chairs I have discussed this with, training small groups of accident investigators from the diving community, while not a bad thing in itself, does not seem like a plausible solution to the wider problem. Given the wide spectrum of potential equipment and the need to have the right person at the right place at the right time, a more generic solution seems necessary. I have identified two key points and generated a statement for each. One concerns the immediate aftermath of the accident. As David Concannon pointed out, people at the site will often do the wrong things with equipment. They will move switches, touch mouthpieces, and not take notice of the right things. And then comes the subsequent investigation.

Here is the statement that will interest the training agencies: "The forum recommends that training agencies provide students with a simple list of instructions that will mitigate errors in evidence preservation commonly made early after a serious incident or rebreather fatality." Now we do not have a list, although the sorts of things that would be on that list have been presented at this meeting. Clearly, I do not want to get into a debate about the exact items on that list. This is a concept. But I would take responsibility under the auspices of the UHMS diving committee to compile the list in conjunction with the people who presented here at this meeting. What I am saying here is that in a rebreather mod 1 course there would be a slide in the course about what happens, what you do if there is an accident and what you do not do in the immediate aftermath. I expect this to be a little more controversial, but I am interested in your views.

MOUNT: I think it is a good idea, but you have to consider different countries and laws. Generally, when an accident has occurred, the legal standpoint is to preserve the crime scene. It is necessary to abide by this. I have no idea how you would develop it.

MITCHELL: My sense is this list is not a complex list. It is more like, "Please do not touch the valves; please do not turn off the mouthpiece; please do not flick switches; please look at and record what the gauges say; but do not interfere."

WALKER: I wonder if maybe this would be better put on the manufacturers than the training agencies with the protocol to contact the manufacturer for specific instructions.

MITCHELL: We are coming to that next. This is when you first get out of the water, Richard. You know what happens, people interfere with stuff before they contact anybody. The manufacturers are not going to be there.

WALKER: Does it need to be anything other than "Do not touch anything" then? My concern is that it inherently makes the other rebreather diver subject to all the discovery and legal and testimony. Now they are caring for evidence and should establish a chain of custody.

MITCHELL: I think you are getting a sense that this is going to be a protocol for a rebreather accident investigation. It is not. It is going to be a few key points of advice that you can fit onto a single slide that say, do not do this, do not do that, these are the obvious errors you can make. And the next slide is going to be getting on to contacting someone who can help you with the right advice straight away.

WALKER: I was concerned when you said writing down pressures and things like that.

MITCHELL: We would take Mr. Concannon's advice.

ANTHONY: I agree fully with the first paragraph statement. I have got some concerns with the second part. Who will develop this? I think you need to make sure you have input from manufacturers and from the people who will be receiving this kit for study.

MITCHELL: I would be happy to take that away. The only problem is we have not actually put it down as an action item for anyone. What I am asking is for this group to trust us to talk to the right people.

ANTHONY: To help you, I have one that has been agreed upon within the UK regulatory bodies that I can give you a template.

MITCHELL: That would be great.

STEVEN SELLERS: I would recommend that we replace the word "rebreather" with "diving" to address the situation where we may be dealing with mixed teams or whatever.

MITCHELL: Except that then the list would be different. I understand what you are saying. With the other thing there, too, we would therefore be recommending to all training agencies do this same thing. I am not sure that all would want to have a slide like that in their underwater diving course.

SELLERS: I think you have covered that with the terminology provided them with a simple list.

MITCHELL: I agree with you, but this is a rebreather forum. I would prefer to leave it as it is. Let me have a show of hands. Who would like me to open this up to the entire diving industry?

UNIDENTIFIED SPEAKER: It is already there.

MITCHELL: I did not see it in the Professional Association of Diving Instructors (PADI) open-water course or rescue-diving course. Who thinks that we should take this from the rebreather realm to the mainstream diving realm? Put up your hands. We will leave it as it is.

DAVID CONCANNON: I agree with Tom Mount. I think this is a good idea. I like the emphasis on simple lists and the simpler the better. I do not think it can hurt anything, and it could be helpful.

MITCHELL: Thank you for that. So we have a legal opinion.

MICHAEL PIZZIO: We have to ensure that divers do not interfere with the evidence.

MITCHELL: I totally agree. I think the message we got from David on the first day was that divers are interfering with the evidence.

GRANT GRAVES: My only issue is with the students. Are we talking about entry level, because if we are going to start teaching people from scratch on closed-circuit, we do not give this information on open-circuit to rescue divers.

MITCHELL: "Entry-level rebreather students?"

GRAVES: Yes, I am questioning "entry-level."

UNIDENTIFIED SPEAKER: What about just "rebreather divers"?

MITCHELL: Hang on. These are students having their first interaction with a rebreather training agency. So they are entry-level students, are they not?

UNIDENTIFIED SPEAKER: I think you should remove "entry-level."

MITCHELL: I think that is reasonable. We will remove "entry-level" and leave "rebreather students."

ANTHONY: Can you take it one step further with "rebreather students and existing divers"? We are a big club, 30,000 people. There are a lot of people who are already trained who need this information.

MITCHELL: I am going to include a footnote to recommend distribution to existing divers, where possible.

MITCHELL: OK. Is there anybody who now disagrees with this statement? That statement is carried unanimously for the record.

The next statement reads, "The forum endorses the concept of a widely notified, centralized, on-call consultation service to help investigators in avoiding errors or omissions in the early stages of a rebreather-accident investigation and to facilitate referral to expert investigative services." This could be achieved via DAN or equivalents in different countries in the world, in conjunction with or as a dedicated website. The point here is that everyone in this room knows if they go diving tomorrow and get decompression sickness, they will ring DAN. That is what we do. If we know that when you have a rebreather accident and you want to get an investigation going, it needs to be dealt with properly, that you also ring DAN, and the DAN person knows which website to refer you to or which person to contact. Then you have solved the problem of needing to have experts present in every single rebreather accident situation. You need a centralized referral service. I think this is a pragmatic solution to the problem, but I would be very interested in hearing from someone from DAN here who may want to comment on it. Is it reasonable to have a sheet of paper at the DAN phone saying if someone calls and says he has a rebreather accident on his hands, this is what you tell them to do? What do you think, Neal?

POLLOCK: Easy in principle. With the incident database we maintain, this is very logical.

ANTHONY: As someone who does investigations, I have often been presented with rebreathers where people have been given expert advice already, and it has made my job an absolute nightmare. So I agree with the principle, but I am worried that when it gets to the expert investigation services that they receive equipment that has been tampered with.

MITCHELL: That is exactly the point. So someone has an accident in the UK. I do not know what phone you have there, if you have a DAN phone. They say, "Do not touch it." You can look it up on the site, but I am going to put you in touch with Gavin Anthony at QinetiQ, and he is going to tell you what to do with this rebreather. The policeman on the site rings the DAN phone and says, "I have a rebreather accident." The person on the end of the DAN phone says, "You need to talk to Gavin Anthony." That is the whole point.

ANTHONY: I think "provided it" comes over in that manner.

MITCHELL: That is the whole intent of what I am saying here.

PETAR DENOBLE: Just to confirm that for the referral operation, I would not qualify experts but compile the list of experts.

MITCHELL: Referral to expert investigative services implies that this centralized on-call service will have the right names to provide. And this is trying to get around the "I got a guy" thing.

NICHOLAS BIRD: I am actually going to go a little bit against my colleagues on this one as the guy who oversees the medical services call center for a few very simple reasons. For me to provide medical information, I can do that. If I provide you more information, I start practicing medicine over the phone for somebody who I do not have a doctor-patient relationship with, and that puts us in a significant position. That is not good. I am just giving a context. If I all of a sudden start providing some medical legal advice, you have got an accident, and you are asking me about an injured person, for which I can say, "You know what, it sounds like you should go to the emergency room," versus "I have got a guy," which I realize — do you want me to create that list of approved people? Do

Figure 2. RF3 pool tryouts. Photo courtesy Jill E. Heinerth.

you want DAN to be responsible for creating and maintaining that list for that industry? That puts a burden on DAN that we really should not get into.

MITCHELL: I hear what you are saying, Nick. That is why I have the word "concept" underlined there. This is an idea for getting around a problem that seems to me to be otherwise unsolvable. Now, whether that central referral source ends up being DAN or just a website, I do not really care. But the concept of a centralized resource is what I am getting at here. It does not have to be DAN. It could be achieved by DAN or equivalents and/or a dedicated website. We are not committing DAN to anything.

BIRD: The other part of this is I am also speaking about conversations I have had with our board, who get nervous about DAN being in any kind of way a legal referral service.

RICHARD HARRIS: As one of the doctors who answers the DAN emergency helpline in the Asia-Pacific region, if DAN, the overseer of this telephone service, agrees that this is something that would work and it is safe for them legally, I think it would be an excellent resource. Because people know that DAN is the organization to call. And it is an excellent central resource that works very well, in my opinion. As one of the people who picks up the phone, I would be happy to give that very simple advice, these are the people you need to talk to, and nothing more specific.

BIRD: Often we do not hear about fatalities or accidents for some time.

MITCHELL: The concept is that you would hear about it because people would know to call you if it was something that DAN decided to take on, but DAN may not. DAN may just decide to host a page on their website or someone else may decide to host a page. What I am asking for here is an endorsement of a concept of a centralized resource.

BIRD: I do not disagree with the concept. I am trying to get down to an operational pragmatism, which is that it is very difficult for us — people know that DAN takes accident fatality information and has for the last 20 years. We still do not get called on most of those. We have got to find out those things. So it is usually not very efficient operationally. So I do not want to say we are going to do this, and it does not work. We have not solved your problem.

MITCHELL: The only way we are going to solve this problem is with a centralized resource. I am putting out the concept here. We are not going to resolve it today. We are not going to identify how that resource is going to be established. We are not going to establish who it is. But I think the idea of a central authority is the way to go.

DREW RICHARDSON: Simon, you can preserve your conceptual idea if you eliminate the last sentence and address the controversy within DAN. There were some good points made here.

MITCHELL: I do not think we should debate this for much longer, because we are not going to establish who it is and how they are going to do it today. It is the concept of being able to contact a centralized resource when you have a rebreather accident for expert advice.

JAMES LAW: I find this idea very good. Having DAN as our first point of contact would be a double benefit since that way they would get the initial notification of a rebreather fatality. I think that would be a great idea to pursue.

MITCHELL: If we agree on this statement, then I can tell you what I am going to be doing. I am going to be chatting with Nick Bird and Dan Orr offline and saying, "Can we make this work for you in any way? Let us talk to David Concannon." If this is not going to work, we will find another way of doing it. I think a centralized resource is our best chance of making sure the right people get involved in the right place.

STEVEN NEUMAN: As a crime scene investigator, this might well be distributed through the sheriffs' association, law enforcement agencies, so that they are made directly aware. Having a lot of outside influences sometimes confuses the investigation. If you can educate law enforcement agencies, it might work better than having DAN hold the responsibility.

MITCHELL: That is a good point. I think the concept though is that once we establish it, the people we would want to educate would be divers so that when they are involved in an accident, just the same way they ring DAN when they are sick, they contact this resource to get advice on management of a rebreather accident.

PAWEL SZOPINSKI: I am just wondering if there is a point of involving manufacturers in such instances where each, for example, manufacturer could offer a point of contact. For example, when there was an accident on a rebreather itself, you could have that information or contact them.

MITCHELL: We will come back to that in the next statement. Is there anybody who disagrees with this statement as it currently exists? There is one person in disagreement. So it is carried by a clear majority.

The next point came out very strongly in several of the manufacturers' presentations: "The forum recommends that in investigating a rebreather fatality, the principal accident investigator invite the manufacturer of the incident rebreather to assist with its evaluation, including the crucial task of data download, as early as is practicable." This would stand whether the principal investigator is a policeman in New Zealand, a sheriff or Coast Guardsman in the United States, or a coroner in the UK. Would anyone like to speak to that?

LOCK: Any of the manufacturers involved in the accident where you have got mixed open- and closed-circuit divers, other download data may be useful in understanding what happened to these.

MITCHELL: If I said "manufacturer of the incident rebreather or any other relevant equipment," would that work?

LOCK: That addresses an issue that Bruce had about data download.

MITCHELL: From computers. Thank you. I personally agree with that modification. Does anyone object to that modification? Can we take a vote on this statement? Is there anybody who disagrees with this statement? Carried unanimously.

Now we are changing track from rebreather accident investigation. I want to go on the record that you could have knocked me over with a feather when that paper handed to me with all those training numbers in it. That was an extraordinary thing, the likes of which we have never had before. My congratulations to you, gentlemen. "The forum applauds and endorses the release of pooled data, not individual agency data that identifies the individual agencies, but pooled data describing numbers of rebreather certifications by training agencies and encourages other agencies to join ANDI, IANTD and TDI in this initiative." Does anyone wanted to speak to this, particularly anyone from any of the other training agencies?

MITCHELL: Drew, do you have anything to say about this?

RICHARDSON: Works for us.

MITCHELL: I was just as blown away by the training accident data that you released at the fatality workshop, and PADI has been very open with their data. All right. Can we have a vote on this? Is there anybody who objects to this statement in its current form? Carried unanimously.

JEFF FRANK: One of the exciting things I saw in this accident investigation presentation was the black boxes included in these machines. I saw several slides where the information was amazing, and a couple where the information trailed off after some period of time. I am wondering if we feel that the standards for data selection and retention are appropriate or if we need standards and/or certifications to put the computers and equipment to make sure that we retain the data after a computer sits on the bottom of the ocean for some time.

MITCHELL: So your statement is something along the lines that we would be specifying some parameters that we would rebreather black boxes to meet in order to be useful to us?

FRANK: Yes. Specifically, I am wondering if we can solve some of the problem of accident investigation with technology. We know it could be turned back on. We know it could be rattled in a Zodiac on the way back to shore. Can we make sure the computer operates in a way to save the data?

MITCHELL: Some of the issues you raise are very specific. What we will do is hold these questions to see where we are at the end of presentation. If we address them now we will not get through the rest of the list.

FRANK: All right. Thank you.

MITCHELL: This is a really important initiative that was raised several times. It is obvious, but by endorsing this statement we are getting it into the public domain in the findings of this workshop: "The forum endorses the DAN worldwide initiative to provide a means of online incident reporting with subsequent analysis and publication of incident root causes." Does anyone want to speak to it? Very good. Carried unanimously.

Now we move into the area of design and testing. The statement reads, "The forum recommends that all electronic rebreathers incorporate data-logging systems that record dive and functional parameters relevant to the particular unit and that allow download of these data. Diagnostic reconstruction of dives with as many relevant parameters as possible should be the goal of this initiative." As a footnote I want to state that an ideal goal would be the establishment of a common format and content for the data that should be collected. This gets to the point that the last speaker was making. If we and/or the manufacturers go down this path, there will need to be some definitions, but it is not our job to establish them today.

ANTHONY: Can we take the word "electronic" out?

MITCHELL: I thought about that, and I put it in because of what the makers of the Halcyon RB80 are going to say when this comes out. To comply, they would have to install an electronic device in their electronics-free rebreather. Do you still think I should take it out?

ANTHONY: I would still like to see it taken out. Because most rebreathers at least have the O_2 monitor. If you have that then you have got some capability of a black box.

MITCHELL: I do not have a strong view. Let us take a vote on the issue of electronic or not electronic. Who would like to see "electronic" taken out of this so it says "all rebreathers"? Who would like to see it stay there as it is? It stays on a majority basis.

PAUL HAYNES: Should it be "all future electronic rebreather designs"? Should it be "all future rebreather designs" so you incorporate the up and coming generations?

MITCHELL: I do not think that is the spirit of it, Paul. I think that what it probably should say is all recreational rebreathers. We would not expect oxygen units being run by militaries. Does anyone have an objection to me inserting "recreational" in there?

UNIDENTIFIED SPEAKER: "Sport diving."

LOCK: What about people getting a hold of commercial military rebreathers and using them? What I mean is keep it to "all rebreathers."

MITCHELL: Does this spill over then with confusion about all rebreathers used by sport divers?

ANTHONY: Before you change that, I am going to object.

MITCHELL: Before I change anything, let us run with more discussion.

NIGEL JONES: I think you should consider adding the word "redundant" to data-logging systems. So the point being is if you have a single data-logging system and it fails, what do you do? So if you are going to go to the trouble of doing it, should you make it redundant so that you always have the data available?

MITCHELL: Nigel, to your knowledge, how many of the current rebreathers have redundant data-logging systems?

JONES: I know of one.

MITCHELL: Can I put that question to Martin Parker?

MARTIN PARKER: We have the capability of doing it. We have never needed it. But we have three processors on the system, so we have the capability. We do record a little bit of information in the controllers, but generally we record all the data in the handset. So we do not have a full redundant system in terms of all the information.

MITCHELL: We will come back to your concern, Nigel.

MOUNT: Would it be more appropriate to say some means of recording it like an external computer?

MITCHELL: Actually, I have a high-level goal with this statement. What we are trying to do here is enable diagnostic reconstruction. I think Bruce Partridge has to be credited with that term. I think that should be our goal.

ANTHONY: I am going to go back to saying "all rebreathers." This is not a sports-diving rebreather forum. It is a rebreather forum. There are military, commercial. There is a range of people here.

MITCHELL: I am going to take that out and say "all rebreathers." I will address the redundant side of it in a moment.

PARKER: I think if you put it in, that is fine. But I have got a feeling that for us to change the format now would be very difficult. For Poseidon to change the format would be quite difficult too. I think it is probably going too far.

MITCHELL: Would you object to it saying "common content"?

PARKER: That is good.

MITCHELL: I am happy with that. My sense, Nigel, on the issue of redundancy, is that I am reluctant to put it in there at this time. I understand that it would be a laudable goal, but let me ask Martin a question. You have had the opportunity to download data on a moderate number of accidents, because you have got a lot of rebreathers out there. In what proportion of cases have you failed to get that data?

PARKER: We have always managed to get the data from the deceased's rebreather. No problem. It was just the one where the data was corrupted on the partner's rebreather.

MITCHELL: I would like it to be noted for the record that the issue of redundancy was raised and that I do not think any of us here would argue that in an ideal world we would have redundancy. But I do not feel inclined to put it in this statement.

UNIDENTIFIED SPEAKER: Put it in a footnote.

MITCHELL: I think that would be a reasonable thing to do.

Is there anybody in here who objects to this footnote statement as it currently reads, "An ideal goal would be to incorporate redundancy and to establish a common content for data to be collected." Objections? The statement is carried unanimously.

The next design and testing statement: "The forum endorses the need for third-party premarket testing to establish that rebreathers are fit for purpose." Ideally, this testing should be to an agreed universal standard and should result in public reporting of a uniform suite of practically important parameters such as canister duration. I would like to open that statement for discussion.

Figure 3. Various rebreathers prepped ready to go diving at Divetech's Inner Space. Photo courtesy Rosemary E Lunn / The Underwater Marketing Company.

KEVIN GURR: Could you add the word “unmanned” in there.

MARK POWELL: Should the “result in” be taken outside of the “ideally” clause?

MITCHELL: Kevin, Martin or Leon, what do you currently do? Do you publicly report the results of your premarket testing?

SCAMMERHORN: It is part of your market plan: achieved scrubber duration under this workload, at this depth, at this water temperature. And you state what standard it was tested to. For example, we use the 14143 and U.S. Navy criteria. We quote both.

MITCHELL: So in other words, if we took that out of the “ideally,” it would not be any imposition on rebreather manufacturers? I like that idea. So what we will do is we will put the …

UNIDENTIFIED SPEAKER: Take out the word “ideally.”

MITCHELL: No, I will wordsmith this a bit. Trust me that I will not change the meaning. It is just a bit hard to word it nicely. So we have taken the public reporting of the results out of the ideal realm and we have put the uniform standard in the ideal realm.

UNIDENTIFIED SPEAKER: I would add “work of breathing.”

OSKAR FRÅNBERG: I was referring to the “unmanned” statement by Kevin Gurr. Practical performance is a pretty big part of the European standards today. If we are going to have “unmanned” there, I think we should have “manned” or just take the “unmanned” away. I mean, just testing a rebreather unmanned is just not doing the whole thing.

MITCHELL: Answer me this, Oskar, or someone who is familiar with the standards, is the premarket third-party testing ever manned?

FRÅNBERG: There is a large part of the standard today that is practical performance.

MITCHELL: So why did Kevin want it to be unmanned?

GURR: You are partially right. I should probably expand on this a little bit. The way it works under 14143 at the moment is the bulk of the work is done under a unmanned environment, and then once the manufacturer is satisfied that you have a fit-for-purpose machine, there is then a section of 14143 that requires some manned analysis. It is not in a military environment. It is divers going out and doing test dives.

MITCHELL: So why do you want it…

GURR: What I was trying to say is that it is very much a premarket thing. It is important just for a safety aspect before anyone gets into any kind of man trials there is a completely unmanned validation.

MITCHELL: Oskar, I am sympathetic to Kevin’s view there. This is not saying that there should not be manned testing. There should be unmanned testing with reporting of the results. As Kevin has outlined, I do not recall seeing informal reports of manned testing being publicly reported. Can you live with that?

ANTHONY: Can I offer clarification? You have two separate things here. The first sentence is, “The forum endorses third-party testing to ensure it is fit for purpose.” That could be unmanned, manned, that could be everything. So make that bit generic. Now, the results that you are going to give are hard, numerical data, and I think that should come from the unmanned aspect because that takes out a lot of variability.

MITCHELL: Nice suggestion.

PARKER: I am not too happy on the “uniform suite of information.” Where are we going to get that uniformity from? Work of breathing, either you meet the standard or you do not. I would go for “canister duration and type of material,” and I would take out “uniform suite.”

MITCHELL: These are just examples. I put “uniform suite” in because of a comment made during the discussion that it would be nice to know the same thing about every rebreather. So that when we line all the rebreathers up, we have the same data. It is a goal. I would be happy to put “results of practically important manned testing” and take out “uniform suite.” Is there anyone who would object to me taking out “uniform suite”? There are a few. Is there anyone who would definitely like me to take out “uniform suite” other than Mr. Parker? Martin, I am sorry.

POLLOCK: Can you solve it by putting it in the “ideally” section?

MITCHELL: No. I think the view is pretty clear.

PARKER: If you are going to have a “uniform suite,” you better just agree here and now.

MITCHELL: Have you guys just started an organization called Rebreather Education and Safety Association (RESA)? You can talk about it there. This is what this forum would like. It is not a mandate that you have to follow. It is endorsing a requirement for third-party testing and should be reported. We would like to know the same things about the units.

JOHN CLARKE: Having an agreed universal standard is, in fact, a good thing. At least for the near future we will have U.S. standards, we will not have the European standard. This would be a really brilliant idea, but I suspect it will be quite a while before we have a universal standard.

MITCHELL: I am very reluctant to disagree with you. Was it your sense from the folks on your chair that people did or did not agree with a uniform standard? Because the sense I got is that there was a general view that a uniform standard is a good idea.

CLARKE: I think the understanding is that there could be more than one standard. Certainly we care a lot about the European standards, but also as somebody indicated, they have to follow the U.S. Navy standard as well.

MITCHELL: Is there anybody who would object? I think what John is signaling here is that in the near future the United States of America might develop their own standard and who is to say that has to be the same as 14143; is that right?

CLARKE: Right. Or who has to do the licensing or it could also be an ISO standard.

MITCHELL: I will buy that argument. Is there anyone here who would object to me taking out that last sentence?

PARKER: How about going to "an internationally recognized standard."

MITCHELL: All right.

PARKER: I am still on the objection of "work of breathing." The breathing effort consists of many issues. What I am worried about is people buying products just on numbers. You can have a slightly higher resistant workload and overall perceived work of breathing. What I do not want people to do is buy products on the wrong numbers. So you are either meeting a European standard, or you are not. You are either meeting it, or you are not.

MITCHELL: Martin, the alternative is no information, and I do not think this meeting is going to accept that. Does this make it any better for you "such as canister duration," and we can take out "type of material." So "such as canister duration, work of breathing qualified by a clear statement of experimental parameters." I do not think it is acceptable to this forum that we just say because people can function without reporting this, we accept them not reporting it at all. I think the feeling of the meeting is that people want to know these things.

PARKER: "Canister duration and material type" should be in there. "Work of breathing" should not.

MITCHELL: I am going to put that one to a vote.

FRANBERG: If we are going to put examples, we should have hydrostatic imbalance as well.

MITCHELL: Shall I just take out these examples?

POLLOCK: Yes.

HEINERTH: No.

MITCHELL: How many people would be happy for me to take these examples out? How many people do not want these examples taken out? It is the majority view. I am going to leave it there.

HAYNES: By referencing these national standards by default you capture these things, do you not?

MITCHELL: We are going to take a vote on this. I know there will be some objections to this. How many people in here object to this statement as it is currently worded? There are some objections. And how many people are in favor of this statement as it is currently worded? It is carried with a clear majority.

This arises from Kevin Gurr's survey data. "The forum acknowledges recent survey data indicating a poor understanding among trained users of rebreather operational limits in relation to depth and carbon-dioxide scrubber durations and, therefore, recommends, one, that training organizations emphasize these parameters in training courses; and two, that manufacturers display these parameters in places of prominence in device documentation and on websites." We have to acknowledge the survey data. Is there anyone who disagrees with these statements in the current form? Carried unanimously.

The next statement speaks to Nigel's outstanding presentation, in my view, this morning. "The forum strongly endorses industry initiatives to improve oxygen measurement technologies and advocates consideration of potentially beneficial emerging strategies such as dynamic validation of cell readings and alternatives to galvanic fuel cells." Does anyone want to speak to this statement? No. We will take a vote. Is there anyone who disagrees with this statement as it is currently written? Carried unanimously.

This is a unique statement as the only one in which we are proposing a research question to the research community. This arose out of Paul Haynes' advocacy for the use of gag straps. In fact, the resulting discussion made it clear that there was a lot of ambiguity around people's perceptions. To my knowledge, there are no data or even substantial practical experience that answers that question for us. This statement says, "The forum identifies as a research question the issue of whether a mouthpiece-retaining strap would provide protection of the airway in an unconscious diver." We need to find a confident ethics committee or an imaginative way of figuring it out. Is there anyone that would like to speak to this?

UNIDENTIFIED SPEAKER: Can we clear full-face masks in that?

MITCHELL: We have a statement about full-face masks coming up next.

PAUL RAYMAEKERS: I was not able to follow the presentation. I just hear that the question has no proof or any evidence that a mouthpiece-retaining strap has any efficiency. We did have a fatality a few years ago where it was clearly proven that when the jaw stress completely falls away a correctly attached gag strap keeps the mouthpiece in place and no water comes in the diver's lungs.

MITCHELL: If I am interpreting correctly saying there, there has been a case that you know of with a gag strap and mouthpiece in place. John, do you want to speak to this?

CLARKE: I think research would include looking at prior history. One case does not mean this has been solved.

FRANBERG: We come from the military community. I think that if we look at our own data from the fatalities, we may find information on the presence or absence of water in the airway.

MITCHELL: I like that idea. So what we need is someone who has perhaps a Naval group with keen, young, research-hungry doctors who can start phoning up every navy in the world. My tongue is in my cheek if I have got a smile on my face. I think there probably may be enough information out there already to form this debate. We have just got to find it. It would be great to have that reported. If someone could compile the cases and report them, I think that would be a pretty powerful case. Is there anyone who objects to this statement in its current form? Carried as unanimously.

The next statement was a result for John's focus group. "The forum recommends that industry and divers interact with the goal of optimizing a full-face mask for use with rebreathers." This is largely on the basis that a full face mask presents a lot of advantages in terms of airway protection. As was mentioned in a number of discussions, there are disadvantages that come with them also, particularly in the realm of rebreather technical diving, and the need for gas switches and in some cases multiple gas switches.

HEINERTH: Unfortunately, this was one of the sessions where we did not have the opportunity for feedback and questions and comments at the end. So I do not know if there was clear consensus.

MITCHELL: If you want to say something, say it now.

HEINERTH: Just that there are many other issues and perhaps this could be worded in a way similar to the last question. It is a research question because there are many downsides to full face masks that need to be examined as well, such as they are not designed for closed-circuit, introduce new failure points, morbidity issues, CO_2 buildup, need for extra gas for flushing, need for training for clearing. There are a lot of things that need to be studied.

MITCHELL: John, would you have any objection to me rewording this into a research question?

ANTHONY: In response to Jill, the military has addressed this over the years. So recommending how to move that technology into more universal aspect is good. Either recommend or make it a research aspect.

MOUNT: I am going to make a comment based on some personal experience. We had a canister break loose at 20 m (66 ft) with a full-face mask. I had to come up, get the open-circuit mouthpiece, and try to keep water in the loop under control. I do not think training rebreather divers on the full-face mask is a necessary process.

UNIDENTIFIED SPEAKER: I was thinking adding appropriate training if you are going to use a full-face mask.

MITCHELL: I do not have any difficulty with an issue for which training is critically important. What we are really getting at here is whether a full-face mask as a concept is a good thing. If we accept that it is a good thing, then training is clearly critical. But the spirit is really trying to get a sense of whether we should be saying to rebreather divers that full-face masks are a good thing for rebreather diving. I think we are one step back from talking about the training. It is a bit like the gag-strap question. We are trying to decide whether these were a good idea or not.

UNIDENTIFIED SPEAKER: The "optimizing" not just the full-face mask itself, but the practices of the closed-circuit divers.

MITCHELL: I think I might take "optimizing" out because that has the expectation of a positive outcome about it. The goal of establishing feasibility is what I am thinking of.

WALKER: I agree wholeheartedly with Jill on this. With respect to our military colleagues, we do use this equipment in a substantially different way. I am not aware of any evidence to prove that in the manner that we use this equipment, a full-face mask offers a clear safety advantage. That would need to be established first. And once that is established or if that is established, we can move on to the need to develop a product. But I would support more of a research focus on this to look at whether or not we are sure before we suggest that a full-face mask does offer more advantages than disadvantages in the way we use rebreathers.

MITCHELL: I am going to change this to the same sort of style as we had before. So, "The forum identifies as a research question the feasibility of a full-face mask for use with rebreathers."

POLLOCK: Should that be "efficacy" rather than "feasibility?" We know it is feasible.

MITCHELL: Yes, you are right, as usual, when it comes to wordsmithing issues.

TERRENCE ADAMS: I am going to fall in line with Tom and Jill on this one. I think for us to recommend the use of a particular thing we have to remember the famous open-circuit debate we had on this topic 15 or 20 years ago.

MITCHELL: I am completely happy with that, and I think that phrasing it this way puts a very cautionary tone on the whole issue of full face masks in rebreather diving.

ADAMS: I want to keep that ability to be able to deny that.

LOCK: You might solve that by adding "sport" or "recreational." We know the military have processes for that.

MITCHELL: I think this is one case where it is reasonable to distinguish between military and recreational.

UNIDENTIFIED SPEAKER: "Sport."

UNIDENTIFIED SPEAKER: I think we are still flirting a little bit on that knife edge with a lot of opinion here. I think it is a really worthwhile thing to look into. We have been diving 20 or 30 years with full-face masks. We love the ability to use communications.

MITCHELL: I do not think there is any suggestion that they can be appropriate in some circumstances. It is just that it is a thing that we recommend for recreational sport rebreathers in general. The sense I am getting from the forum is this is something we would like more engagement with the people who know how to use them before we move forward with this. Now we have got one more very important statement to do. This reads, "The forum identifies as a research question the efficacy of full-face masks for use with sport rebreathers." Is there anyone who objects to this in its current form?

UNIDENTIFIED SPEAKER: Efficacy does not mean anything.

MITCHELL: It does. It is basically saying that there has been a discussion at this forum that gives a sense that they are not something that we think are generalizable across the rebreather diving community and that we need more information, experience with it. Anyway, the vote has been taken.

This is one that is important and potentially controversial. "The forum recognizes and endorses the industry and training agency initiative to characterize recreational and technical streams of rebreather diver training. These groups will have different working envelopes, training and equipment needs." This was discussed quite a lot in the last session that was chaired by Phil and Jill. Is there anyone who would

Figure 4. Optima CCR. Photo courtesy Richie Kohler.

like to speak to this? Is there anyone who objects to the concept?

STEVE LEWIS: I think that we have already established that what everyone does here is not military, scientific, or commercial. So we are doing recreational diving, and recreational diving kind of falls into sport diving and technical diving. It is not a big point, but everyone else has been nitpicking so I figured I had better do it.

MITCHELL: Who are you speaking about in particular? I think the reason for this statement is that these are terms that are going to be brought higher and higher in our consciousness by the training organizations and the manufacturers. This is a route that they want to go down and a distinction that they want to make. It is been raised here a number of times and this is essentially a recognition of it.

WALKER: Can we pull the word "working" out and change it to "operational" so we stay away from that whole OSHA, military, scientific issue.

MITCHELL: "Different operational." Mark Caney, do you want to say anything about this?

MARK CANEY: I like it.

MOUNT: I have a question here. Who would these working groups be? Would they be the training agencies themselves and the manufacturers?

MITCHELL: We are referring to the groups of divers, so recreational divers and technical divers will have different operational, training and equipment needs. We heard in the previous session that there was a defined set of parameters.

MOUNT: Sorry, I misunderstood the statement.

HARRIS: Do you want to put "sport rebreather diver training"?

MITCHELL: Anyone else want to speak to this statement?

ANTHONY: I have one concern with this, and it is a safety concern. That is the fact that the macho aspect will force people to say, "I want to be technical. I want to go down that route." I think there is much more of a sliding scale. You do not go up to a point as recreational and then suddenly flip to being technical. You can progress slowly through that. I think there is a safety concern here that you may inadvertently push people to do things that they do not want to because you put certain names there.

MITCHELL: Jill, do you want to speak to that?

HEINERTH: I would suggest that this statement does the exact opposite, that it recognizes that particular equipment is good for particular types of diving. In the recreational envelope, "I have got a problem, therefore I bailout and go to the surface." That equipment should not allow for a sliding scale between those two entities. I like the statement.

BLETSO: I think all the training agencies are doing that naturally. They have got recreational training and technical training.

MITCHELL: As I have pointed out, this is kind of one of those statements of the obvious, but this is the first rebreather forum we have had since that distinction was made, and hence, the desire for the statement to be made. I think that is specific terminology that is being proposed as technical. Is that correct, Mark?

CANEY: Yes, there are. I think within the sport-diving community there is a distinct understanding of the terms recreational and technical, so this is a good definition as it stands.

ANDREW FOCK: What exactly do you mean by "endorses"?

MITCHELL: That we agree with it. We do not think it is a bad idea. So presumably this might be a unanimous decision then.

FOCK: We will see.

BARRY COLEMAN: There may be a question with regard to what is technical with sport rebreathers. Some may claim that if you are on a rebreather and bailing out to a side cylinder that is technical. Are we taking the recreational and technical from the open-circuit and trying to apply it to rebreather diving where there could be arguments that this is technical in itself, bailing out, whether you are bailing out to turning a switch on the mouthpiece or you are actually bailing out to a side cylinder? Could there be a problem with any of this?

MITCHELL: I do not know if any of the people from the training and operations forum want to speak to that, but my understanding is that there is a very specific definition of what recreational rebreather is, and that definition was displayed during the session. I do not have it here, but there is a set of criteria that defines recreational as distinct from technical. Would you like to speak to that, Mark or Jill?

CANEY: Yes. Again, I would say there is a fairly clear understanding of what these two things are. I think the important thing about this statement is it is recognizing the fact that now as opposed to when we had the last one of these forums there is such a thing as a recreational rebreather user as opposed to what we call a technical rebreather user. And this committee recognizes that delineation and the fact that they have different operating envelopes and different needs.

MITCHELL: I think we will call that discussion closed now. I am going to ask for all those who disagree with this statement in its present form to put up their hands. So there are some, but it is a clear minority. So that statement is adopted by a clear majority. That is the end of the session. I congratulate this forum on a remarkably mature discussion completely absent of vitriolic abuse and other forms of negative argument. I think it has been a fabulous event. I would like to offer my thanks once more to the organizing organizations.

PARKER: Just one question. I brought up the subject about solo diving and diving with a buddy, and it seems like we are not going to get an idea from this forum, but can we show hands up who agrees that rebreather diving should be done in pairs? Show of hands, please. Pairs or teams. Please put your hands down. Everybody who thinks that rebreather diving should be done solo.

UNIDENTIFIED SPEAKER: "Could."

PARKER: "Rebreather diving could be done solo." Thank you. Do you think that is worth putting up there as a motion?

MITCHELL: It is probably too late now. But, for the record, what we just showed there is that a clear majority of the participants of the forum indicated a preference for buddy diving when using a rebreather, but it is also clear that a significant portion of the forum participants believe that you can dive solo but not necessarily that you should dive solo. That would be my interpretation.

RICHARD VANN: It remains for me to close the meeting, which I will do shortly. On behalf of AAUS, DAN, PADI, a few more acknowledgments. We appreciate the critical support of PADI personnel, Dawn Azua, Adrianne Miller, Janelle Hamm, Dan Machum, Tom Hedlick, and Nicole Sherman. Similarly, from DAN and Duke, Jenna Wiley, Mitch Mackey, Gene Hobbs and Dr. Dawn Kernagis. These individuals kept all of the rooms running smoothly. We also thank Kim Farkas for recording notes and Roz Lunn for organizing the venue. Finally, thank you all for your active participation. Rebreather Forum 3.0 is now closed.

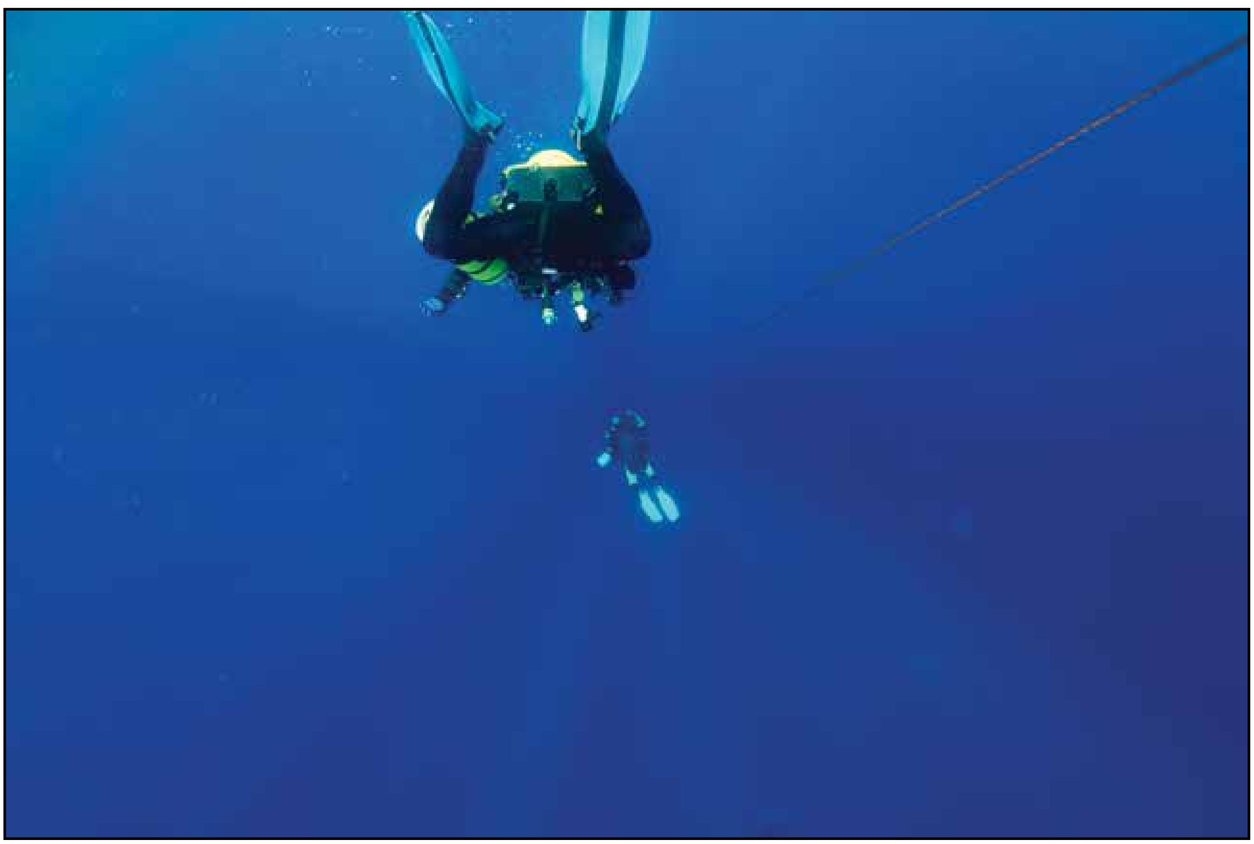

Figure 5. HMS Hermes*, Sri Lanka. Photo by Andrew Fock.*

AFTERWORD

Richard Vann
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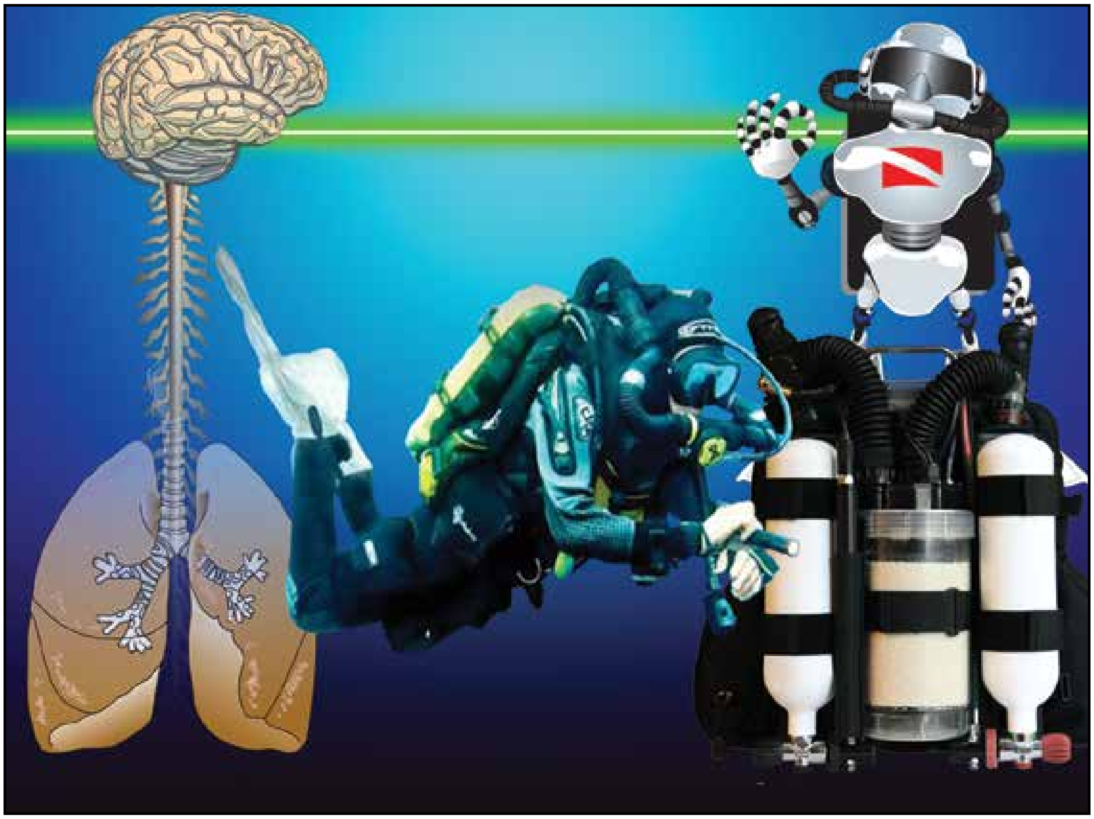

I touch a hot stove and unconsciously withdraw my hand under control of an autonomous spinal reflex. I could consciously withdraw my hand by thinking, "This stove is hot. Move fast to avoid a burn." Too late, I am burned. Consciousness is so much slower than reflex.

I have conscious and unconscious control of my respiratory system. Unconscious control occurs through my brainstem and spinal cord and autonomously adjusts my ventilation to maintain physiological levels of oxygen and carbon dioxide. This process evolved in air at sea level, but I can consciously override it by holding my breath or hyperventilating. When I free-dive, this sometimes gets me in trouble.

A rebreather is an external respiratory system with elementary oxygen sensors, bumpy control of inspired oxygen, and an occasional carbon dioxide sensor. I must consciously monitor my sensor readouts to ensure proper operation and concentrate on how I feel to avoid carbon dioxide toxicity. A few divers may have the "right-stuff" to rebuild their rebreathers at 100 msw and do mental Dalton's Law calculations to check their oxygen partial pressure after an inert gas flush, but these are uncommon capabilities, and statistics and experience demonstrate most rebreather deaths are associated with "easy" things – no predive checklist, no predive prebreathe, and diving with failed equipment. Moreover, even the most experienced and technically competent rebreather diver can be overwhelmed by task loading or clouded consciousness under the effects of hypoxia, oxygen toxicity, carbon dioxide poisoning, nitrogen narcosis, hypothermia, or HPNS.

Rebreather divers who are careless about predive preparation, become unfocused, or have an unlucky day are removed from the gene pool, but this is not desirable. The best answers are good predive preparation and equipment that self-monitors, provides attention-grabbing warnings, and takes corrective action when feasible for busy or confused divers. Self-monitoring rebreathers will develop slowly, and predive attention to detail is the immediate safety challenge that educators must instill in their students and on which dive operators must insist.

GLOSSARY

Revised and expanded from the glossary of* The Basics of Rebreather Diving *by Jill Heinerth (2014).

A

Abort — The termination of a dive and immediate commencement of a return to the surface. It may or may not involve a bailout.

Absolute pressure — The total pressure imposed by the depth of water plus the atmospheric pressure at the surface.

Absorbent pads — Absorbent material placed in a breathing loop; used to soak up moisture caused by condensation and metabolism.

Accumulator — A small chamber that provides a collection vessel to ensure proper gas flow of oxygen to a solenoid valve.

Active-addition — A rebreather gas-addition system that actively injects gas into the breathing loop (such as a constant-mass flow valve in certain kinds of semiclosed rebreathers).

Air — A naturally occurring gas that makes up the earth's atmosphere and contains approximately 78 percent nitrogen, 21 percent oxygen and 1 percent various trace gases.

Air embolism — See *gas embolism*.

Alveolar exchange — Diffusion of oxygen into the blood and removal of CO_2 from the blood in the alveoli of the lungs.

Alveolus — The terminal end of the respiratory tissue where gas is exchanged with the blood.

Ambient pressure — Pressure of the surrounding medium, liquid or gas that is in contact with an object.

Anatomical dead space — The airway superior to the alveoli comprised of the upper airways where no gas exchange occurs.

Anoxia — The absence of oxygen; see also *hypoxia*.

Figure 1. Analyze every onboard and bailout cylinder, and mark them properly. Photo courtesy Jill Heinerth.

Apnea — Cessation/absence of breathing.

Argon — A colorless, odorless gas that does not react chemically under standard conditions but can induce narcosis with greater potency than nitrogen. During the production of oxygen by certain methods, argon may be present in more than trace amounts, presenting an increased inert gas narcosis potential. Also sometimes used as a drysuit inflation gas.

As low as reasonably practicable (ALARP) — A safety system principle that the risk associated with a given aspect should be as low as reasonably practical.

Ascent — In the direction of reduced pressure; whether undertaken in in a hyperbaric/hypobaric chamber or upward movement through the water column.

Atmosphere (atm) — A unit of pressure equivalent to the mean pressure exerted by the earth's atmosphere at sea level, or by 33 fsw (10 msw), equal to 1.0 bar or 14.7 psi.

Atmospheres absolute (ATA) — The absolute pressure as measured in atmospheres.

Automatic diluent valve (ADV) — A mechanically-activated valve that adds diluent gas when increasing pressure associated with descent or lowered volume triggers the device.

Axial scrubber — A type of CO_2 absorbent canister design. In this design, the gas flows through the canister in a linear fashion from one end of the canister to the other.

B

Backplate — A plate made of stainless steel, aluminum or acrylonitrile butadiene styrene (ABS) plastic that attaches to a rebreather and allows for the use of a webbed or soft harness system.

Bailout — An abort involving the use of an alternate life-support system (usually in response to a failure of the primary life-support system and often involving open-circuit as the alternative life support).

Bailout gas — Breathing gas supplies carried by the diver to allow for an abort when the primary life-support system has failed, often supplied with open-circuit equipment.

Bailout valve (BOV) — See *integrated open-circuit regulator*.

Bar — A unit measure of pressure, equal to 0.987 atm or 15.5 psi.

Barotrauma — A pressure-related injury.

Figure 2. Bailout valve (BOV). Photo courtesy Jill Heinerth.

Booster — See *gas booster*.

Bore — The internal diameter of a hole, pipe or hose.

Bottom out (counterlung) — To reach the bottom; in the case of rebreathers, a term used to refer to the situation when a rebreather counterlung becomes completely collapsed after a full inhalation.

Bottom time — The time elapsed from leaving surface at the start of a dive until leaving the deepest part of the dive (bottom) to begin an ascent back to the surface.

Boyle's law — A gas law that describes how the volume occupied by a given number of gas molecules is inversely proportional the pressure of the gas.

Breakthrough — The point at which a CO_2 absorbent canister fails to remove CO_2 at the rate it is entering the canister, allowing some to be re-inspired. The fraction of inspired CO_2 normally rises quickly once breakthrough is reached.

Breathing bag — See *counterlung*.

Breathing hose — Large-bore hoses in a rebreather breathing loop through which the breathing gas travels.

Breathing loop — The portion of a rebreather through which gas circulates, usually consisting of a mouthpiece, breathing hose(s), counterlungs, non-return valves and a CO_2 absorbent canister.

Breathing simulator — Device used for the unmanned simulation of a divers breathing and respiration.

Buddy lights — Warning lights that indicate system status (such as life-threatening oxygen levels) that are usually visible to a buddy diver.

Buoyancy control device (BCD) — An inflatable bladder that allows a diver to precisely adjust buoyancy.

C

Calibration gas — A gas of a known composition used to calibrate gas sensors, particularly oxygen and carbon-dioxide sensors.

Carbon dioxide (CO_2) — Waste gas generated by the process of metabolism and exhaled by the diver into the breathing loop.

Cardiopulmonary — The heart and lungs as a unified system.

Catastrophic loop failure — A complete failure of the breathing loop of a rebreather such that it cannot be recovered and used for life support in closed-circuit mode; usually occurring from a ripping or tearing and subsequent flooding of a unit or a failure of the CO_2 absorbent canister.

Central nervous system (CNS) — The human brain, spinal cord, and associated major neurological pathways that are critical for basic life-support processes, muscular and sensory systems.

Central nervous system oxygen toxicity — A serious form of oxygen toxicity, usually caused by exposure to breathing mixtures with an oxygen partial pressure in excess of 1.6 atm (162 kPa). Symptoms may include visual disturbances, hearing anomalies, nausea, twitching, dizziness, and severe convulsions.

Chain of custody — Refers to the chronological documentation that captures the seizure, custody, control, transfer, analysis, and disposition of physical or electronic evidence, typically for legal purposes.

Channeling (of scrubber canister) — A condition in which improper packing or excessive settling forms channels that allow some CO_2 to pass through an otherwise functional CO_2 absorbent canister without being absorbed.

Check valve — A one-way, non-return valve that directs gas to move in only one direction through the breathing loop.

Closed-circuit rebreather (CCR) — A type of rebreather that usually includes some form of oxygen control system and generally only vents gas upon ascent.

CO_2 absorbent — A material that chemically binds with CO_2 molecules (e.g., Sodasorb, Drägersorb®, lithium hydroxide, Sofnolime®, Micropore ExtendAir, etc.).

CO_2 absorbent canister — A canister in the breathing loop containing CO_2 absorbent.

CO_2 retention — Condition in which arterial CO_2 is seen to increase in divers due to insufficient ventilation, excessive dead space in the breathing loop, or ineffective CO_2 scrubber filtration.

Figure 3. Cartridge containing carbon-dioxide absorbent material. Photo courtesy Jill Heinerth.

CO_2 sensor — Any sensor that produces a signal related to carbon-dioxide pressure or concentration.

Condensation — Water that forms when water vapor cools and condenses to form liquid droplets. In a rebreather, heat conduction through the breathing hoses and other components of the breathing loop lead to condensation inside the breathing loop. This process may be exacerbated by materials with greater heat conductivity and lessened with insulation of the breathing loop components.

Constant mass flow valve — A type of valve that allows a constant mass of gas, thus a constant number of gas molecules, to flow at a fixed rate.

Constant volume flow — A type of valve that delivers a constant volume of gas, thus a variable number of gas molecules, to flow independent of ambient pressure.

Controller — Any electronic or mechanical system used to maintain the concentration of oxygen in a rebreather.

Counterlung — A collapsible bag connected to a rebreather breathing loop, which expands as a diver exhales and collapses as a diver inhales.

Cracking pressure — The pressure differential at which a valve opens, enabling gas flow. In the case of rebreathers, the pressure inside the breathing loop relative to the surrounding ambient pressure at which an automatic diluent valve (ADV) opens enabling gas flow into the breathing loop, or an overpressure relief valve opens allowing excess gas to escape.

Cubic feet (ft^3) — A unit measure of volume, defined as the space occupied by a cube one foot on each side; 1 ft^3 = 28.3 L.

Current limited (oxygen sensor) — A condition in which a change in the load applied to a sensor is not met with a change in the current supplied by the sensor.

D

Dalton's law (of partial pressures) — A gas law that describes how the total pressure exerted by the mixture of gases is equal to the sum of the partial pressures of individual gas constituents.

Figure 4. Danger. Rebreather diving is more dangerous than open-circuit diving and should be undertaken with a high level of respect and diligent safety protocols. Photo courtesy Jill Heinerth.

dcCCR — See *mCCR*.

Decompression dive — Any dive that requires staged stops during ascent (determined by the decompression algorithm used).

Decompression illness (DCI) — Injury that includes arterial gas embolism (AGE) and decompression sickness (DCS).

Decompression model/algorithm — Mathematical algorithm used to compute a decompression schedule. A variety of computational models and derivatives are available in tabular or dive computer form.

Decompression schedule — A set of depth/time/breathing-gas composition relationships and instructions for safely controlling the ascent in an effort to reduce the probability of decompression sickness.

Decompression sickness (DCS) — An injury seen especially in divers, caused by the formation of inert gas bubbles in the blood and tissues following a sudden drop in the surrounding pressure, as when ascending rapidly from a dive, and characterized by severe pains in the joints, skin irritation, paralysis, and other symptoms.

Decompression table — A tabulated decompression schedule.

Demand regulator — A valve that delivers gas from a pressurized source at or near ambient atmospheric pressure when the diver inhales.

Diaphragm — A large dome-shaped muscle separating the thoracic cavity from the abdominal cavity, the contraction of which draws gas into the lungs. In the case of underwater breathing apparatus, a flexible gas/liquid impervious barrier that responds to external pressure typically initiating the opening of a valve.

Diffusion — The process by which molecules move from a region of high concentration to a region of low concentration.

Diluent — A gas other than oxygen that is used in a rebreather to reduce the oxygen fraction in the breathing mixture.

Diluent purge valve/diluent addition valve — A manual valve used to add diluent gas to a breathing loop, usually through the counterlung or a gas block assembly.

Display integrated vibrating alarm (DIVA) — An LED heads-up display module mounted close to the diver's mask, offering information about various states of the rebreather such as PO_2; this style includes a vibrating warning alarm when oxygen levels are unsafe.

Figure 5. Gauges should be checked every one to four minutes. Photo courtesy Jill Heinerth.

Dissolved gas — Gas dissolved in a liquid/body tissues.

Downstream — A relative direction with respect to the flow of gas through the breathing loop of a rebreather; the direction of travel of the diver's exhaled gas. See also *upstream*.

Downstream check-valve — A check-valve typically located near the mouthpiece of a rebreather that prevents subsequent re-inhalation of exhaled gas by directing it through the CO_2 scrubber canister.

Drowning — The process of asphyxiation caused by the aspiration of a liquid.

Dump — Venting gas from the breathing loop via counterlung dump valves or by venting orally past the mouthpiece assembly.

Dynamic setpoint — A setpoint that changes to optimize gas use, no-stop time and other consumables and dive variables. The dynamic setpoint may be determined by an electronic system or modified manually by a diver.

Dyspnea — Difficult or labored breathing. See also *hypercapnia*.

E

eCCR — An electronically-controlled closed-circuit rebreather in which an electronics system is used to monitor oxygen levels, add oxygen as needed and perform other tasks such as warning the diver of developing problems through a series of audible, visual and/or tactile alarm systems, calculating decompression schedules, and performing various other functions.

Elastic load — A load on the respiratory muscles originating from the rebreather and/or diving suit. Materials in the suit and rebreathing bag may restrict breathing. As the diver breathes, the volume of rebreathing bag(s) changes, making the depth of the bag(s) change. This depth change means a change in pressure. Since the pressure change varies with bag volume it is, by definition, an elastic load.

Electronically-monitored mSCR — A mechanical SCR with electronic monitoring. Electronics are used to inform the diver of PO_2 as well as provide warnings and status updates, however the gas control is manually controlled by the diver.

Emphysema — 1) A condition in which the pulmonary alveoli are enlarged and damaged, causing labored breathing. 2) A condition in which air is abnormally present within the body tissues.

EN 14143 — A CE standard for minimal requirements to sell a rebreather in Europe.

Endurance (of scrubber) — The time for which a CO_2 scrubber operates effectively. The duration varies with individual size, workrate, scrubbing material, depth, and ambient temperature.

Enriched air nitrox (EAN) — A gas mixture consisting of nitrogen and oxygen; containing more than 21 percent oxygen.

Equivalent air depth (EAD) — A depth value derived from a formula used to help approximate the decompression requirements of nitrox. The depth is expressed relative to the partial pressure of nitrogen in normal breathing air.

Figure 6. Loop check. Richie Kohler checks the non-return valves in his loop. Photo courtesy Jill Heinerth.

Figure 7. Mixed teams of CCR and open-circuit divers need to conduct rebreather familiarization and safety drills prior to diving. Photo courtesy Jill Heinerth.

Equivalent narcotic depth (END) — A depth value derived from a formula used as a way of estimating the narcotic effect of a breathing mixture such as heliox or trimix. The depth is expressed relative to the partial pressure of nitrogen (and/or other gas constituents with narcotic properties) in normal breathing air.

Ergometer — A device for exercise testing, typically a cycle or treadmill.

eSCR — An electronic semiclosed-circuit rebreather in which an electronics system is used to monitor oxygen levels, add oxygen as needed and perform other tasks such as warning the diver of developing problems through a series of audible, visual and/or tactile alarm systems, calculating decompression schedules, and performing various other functions..

Eucapnia — The condition in which the carbon dioxide of the blood is normal.

Eupnea — Normal respiration (as opposed to dyspnea).

Eustachian tube — The canal connecting the middle ear and the throat, enabling equilibration of pressure between the external and outer ear. Also known as auditory tube.

Evaporative cooling — The heat energy expended to convert liquid water to gaseous state. Evaporative heat loss results from humidifying inspired gases and the evaporation of sweat on the skin.

Excursion — The restricted time and/or distance movement of a diver either upward, downward or horizontally.

Exhalation breathing hose — The limb of the breathing loop directly downstream of the mouth.

Exhalation counterlung — The counterlung downstream of the diver's mouthpiece, into which the diver's exhaled breath is expired.

Exothermic reaction — A chemical reaction that produces heat as a by-product. The absorption of CO_2 by the scrubber canister absorbent is an exothermic reaction.

Expiration — The act of exhaling gas from the lungs.

Extraction ratio — The relationship between the amount of gas ventilated and the amount of oxygen extracted by the body from that gas. As a general rule an extraction ratio of 22.5:1 may be assumed, i.e., for every 22.5 L of gas ventilated, 1.0 L of oxygen will be extracted for metabolic purposes.

F

Failure mode, effect, and criticality analysis (FMECA) — Summarizes the study of all components that could fail and identifies the type of failure, the probability, and severity as well as possible causes of the failure and mitigation and emergency procedures.

ffw — Water depth as measured in feet of freshwater.

FHe — The fraction of helium in a gas mixture.

Floating setpoint— See *dynamic setpoint*.

Flush (as in flushing the loop) — Replacing the gas within the breathing loop by injecting gas and venting bubbles around the edge of the mouthpiece or through a vent valve.

FN_2 — The fraction of nitrogen in a gas mixture.

FO_2 — The fraction of oxygen in a gas mixture.

Fraction of gas — The percent of a particular gas constituent in a gas mixture.

Fraction of inspired gas — The fraction of gas actually inspired by the diver.

Fraction of inspired oxygen (F_IO_2) — The fraction of oxygen inspired by the diver. In semiclosed-rebreather operation, this figure is calculated using a formula that takes into account the diver's metabolic consumption rate (usually based on workload).

fsw — Water depth as measured in feet of seawater.

Full-face mask (FFM) — Mask system that encloses the entire face and includes a mechanism to supply breathing gas, in contrast with a half mask, whereby only the eyes and nose are typically covered.

G

Galvanic fuel cell sensor — An electrochemical transducer that generates a current signal output that is both proportional and linear to the partial pressure of oxygen in the sample gas. Oxygen diffuses through a sensing membrane and reaches the cathode where it is reduced by electrons furnished by simultaneous oxidation of the anode.

Gas booster — A mechanical device for transferring gas from one pressure vessel into another while concurrently increasing (boosting) the gas pressure within the receiving pressure vessel.

Gas embolism — A pathologic condition occurring in the body when bubbles of air are forced into the circulation and gain access to the arterial system causing blockage of blood flow.

Gas exchange — See *diffusion*.

Gas laws — Mathematical descriptions of the relationship between pressure, temperature and volume.

Gas narcosis — See *narcosis*.

General gas law — Boyle's and Charles' law combined.

H

Harness — The straps and/or soft pack that secures the rebreather to the diver.

Heads-up display (HUD) — An LED or other visual display module (e.g., an LCD display) mounted close to the diver's mask offering information about various conditions within rebreathers, such as PO_2.

Heliox — A binary gas mixture consisting of helium and oxygen.

Helium (He) — An inert gas used as a component of breathing-gas mixtures for deep dives because of its very low density and narcotic potency.

Hemoglobin — The oxygen-carrying compound in red blood cells.

Henry's law — A gas law that describes how gas that will dissolve in a liquid in proportion to the partial pressure of the gas over the liquid.

Hydrophobic membrane — A special membrane that allows gas to flow through it, but serves as a barrier to water.

Hydrostatic imbalance — See *static lung load*.

Hyperbaric — Condition of elevated pressure.

Hyperbaric chamber — A pressure vessel usually used for purposes of testing equipment or for use in hyperbaric medicine or research. See *recompression chamber*.

Hyperbaric medicine — Also known as hyperbaric oxygen therapy, is the medical use of oxygen at a higher than atmospheric pressure.

Figure 8. Heads-up display (HUD). Photo courtesy Jill Heinerth.

Hypercapnia/hypercarbia — Elevated levels of CO_2 in the body due to inadequate breathing, generally induced by elevated respiratory loads and/or inspired CO_2. The level of CO_2 maintained varies from person to person (e.g., CO_2 retainers maintain relatively high levels). Effects of hypercapnia may include shortness of breath, headaches, migraines, confusion, impaired judgment, augmented narcosis, panic attacks, and loss of consciousness. Dangerous levels can be reached while the diver remains unaware. Recovery may take many minutes under optimal conditions.

Hyperoxia — A concentration of oxygen in the breathing mixture that is not tolerated by the human body, generally occurring when the inspired PO_2 rises above about 1.6 ata (162 kPa). See also *central nervous system oxygen toxicity*.

Hyperoxic linearity — The condition that an oxygen sensor is linear at partial pressures of oxygen above the highest calibration point.

Hyperpnea — Increased respiratory rate or breathing that is deeper than that seen in resting subjects. Hyperpnea is a normal response to exercise.

Hyperventilation — Increase in rate and/or volume of respiration.

Hypocapnia — A physiological state in which the systemic arterial carbon-dioxide partial pressure is low; symptoms may include finger tingling, muscle spasms, dizziness, loss of consciousness. Commonly caused by hyperventilation (over breathing).

Hypothermia — Condition of low body temperature, defined by a core temperature falling below 35°C (95°F), substantially below the normal core temperature range of 36.5°C-37.5°C (97.7°F-99.5°F). Reaching a state of frank hypothermia is very unlikely in normal operational diving.

Hypoxia — A concentration of oxygen in the breathing mixture that is insufficient to support human life, generally occurring when the inspired PO_2 drops below about 0.16 ata (16.2 kPa).

I

Ideal gas law — A gas law that defines the relationships among pressure, temperature, volume and quantities of substance of any ideal gas.

Inert gas — A gas that plays no role in metabolism (e.g., nitrogen or helium).

Inert gas elimination — The transfer of inert gas under the influence of a pressure gradient from the tissues to the blood to the lungs, from which it is exhaled. Also called inert gas washout.

Inert gas uptake — The absorption of inert gas from the lungs into bodily tissues under the influence of a pressure gradient. Also called inert gas absorption.

Inhalation — The process of inspiring gas into the lungs.

Inhalation breathing hose — The hose of a rebreather breathing loop directly upstream of the mouth.

Inhalation counterlung — The counterlung upstream from the diver's mouthpiece block, from which the diver's inhaled breath is drawn.

Inner ear — Portion of ear contain semicircular canals a cochlea; involved in both hearing and balance.

Integrated open-circuit regulator — An open-circuit regulator built into the mouthpiece assembly that allows a diver to switch from closed-circuit mode to open-circuit without removing the mouthpiece from their mouth. When the loop is closed, the BOV activates, supplying open-circuit gas directly from the onboard diluent tank (in a closed-circuit rebreather) or supply gas cylinder (in a semiclosed-circuit rebreather).

Isobaric — Condition of unchanging pressure.

L

Light-emitting diode (LED) — A small, low-power light source; often used for warning lights on rebreathers.

Liquid crystal display (LCD) — An energy-efficient display that relies on the light modulating properties of liquid crystals; often used for displaying data on rebreathers.

Lithium hydroxide (LiOH) — A type of CO_2 absorbent material.

Loop vent valve — A type of overpressure relief valve that allows excess gas and accumulated water in the breathing loop to be vented.

M

M-value — The maximum theoretical supersaturation level a compartment (tissue) can experience above which gas will come out of solution to form bubbles.

Manual bypass valve — A valve on a rebreather that allows the diver to manually inject gas into the breathing loop.

Figure 9. Loop weights can help bring down a floating loop. Photo courtesy Jill Heinerth.

Figure 10. Safety stops may be conducted using a lift bag (DSMB) in open water. Photo courtesy Jill Heinerth.

Manual diluent addition valve — The valve on a rebreather that allows diluent gas to be manually injected into the breathing loop.

Manual oxygen addition valve — The valve on a rebreather that allows oxygen to be manually injected into the breathing loop.

Maximal voluntary ventilation (MVV) — The greatest respiratory minute volume that a person can produce during a short period of extremely forceful breathing.

Maximum operating depth (MOD) — The maximum operating depth of a breathing gas before reaching a predetermined PO_2, usually 1.4 ata (142 kPa) or higher and/or narcotic potency. This depth is determined to safeguard the diver from oxygen toxicity and nitrogen narcosis.

mCCR — Diver-controlled closed-circuit rebreather. A manually operated rebreather that requires the diver to monitor oxygen levels and manually inject oxygen as needed to maintain an appropriate setpoint. Also known as a manual CCR.

Metabolism — The physiological process whereby nutrients are broken down to provide energy. This process involves the consumption of oxygen and the production of CO_2.

mfw — Water depth as measured in meters of freshwater.

Middle ear — Air-filled cavity behind the tympanic membrane (eardrum). The pressure in this cavity is equalized with changing ambient pressure while diving.

Middle-ear squeeze — A squeeze resulting from the inability to equalize pressure in the middle ear via the Eustachian (auditory) tube.

Mixed gas — A breathing medium containing oxygen and one or more inert gases synthetically mixed. Typically refers to a breathing medium containing a fraction of helium.

Mixed-gas rebreather — A rebreather that contains a gas mixture other than pure oxygen in the breathing loop.

Mouthpiece (of CCR) — The portion of a rebreather breathing loop through which the diver breathes. This usually includes a way to prevent water from entering the breathing loop and sometimes includes an integrated open-circuit regulator.

Mouthpiece-retaining strap — A flexible adjustable strap attached to a rebreather mouthpiece assembly to reduce the likelihood of dropping the mouthpiece in the event of loss of consciousness.

msw — Water depth as measured in meters of seawater.

Myopia — A vision deficiency in which light rays focus in front of the retina (nearsightedness); can be induced after prolonged exposure to elevated inspired oxygen partial pressures as can occur during multiple consecutive days of rebreather diving with an elevated PO_2 setpoint.

N

Narcosis — A state of altered mental function ranging from mild impairment of judgment or euphoria to complete loss of consciousness. Typically experienced by people while breathing an elevated partial pressure of a gas such as nitrogen or CO_2.

Nitrogen — A colorless, odorless, tasteless, non-toxic inert gas comprising approximately 78 percent of the atmosphere.

Nitrox — See *enriched air nitrox.*

No-decompression dive — Any dive that allows a diver to ascend directly to the surface without the need for staged decompression stops.

No-decompression limits — Maximum times at given depths from which direct ascent to the surface is allowed by a given algorithm — that is, with no obligatory decompression stops.

Normoxic — A breathing gas with an oxygen fraction equivalent to that of air at one atmosphere (PO_2 0.21 ata; 21.3 kPa).

Notified body — An independent agent that acts as the certifying authority and verifies that equipment testing was conducted in compliance with applicable requirements.

O

Offboard diluent — A diluent gas supply that is attached externally to a rebreather.

Offboard oxygen — An oxygen supply that is attached externally to a rebreather.

Onboard diluent — A diluent gas supply that is integrally mounted on a rebreather.

Onboard diluent regulator — A first-stage regulator attached to the onboard diluent cylinder of a rebreather.

Onboard oxygen — An oxygen supply that is integrally mounted on a rebreather.

Onboard oxygen regulator — A first-stage regulator attached to the onboard oxygen cylinder of a rebreather.

Open-circuit scuba (OC) — Self-contained underwater breathing apparatus where the inhaled breathing gas is supplied from a high-pressure cylinder to the diver via a two-stage pressure-reduction demand regulator, and the exhaled gas is vented into the surrounding water and discarded in the form of bubbles.

Optode — An optical sensor device that measures a specific substance usually with the aid of a chemical transducer.

Organic light-emitting diode (OLED) — An electronic display type that does not use a backlight but instead uses an array of colored LEDs, often allowing for greater contrast in low-light applications such as diving.

Otitis media — Inflammation of the middle ear.

Overpressure relief valve (OPV) — A valve designed to allow gas to flow from a higher-pressure space to a lower-pressure space at a particular cracking pressure. In the case of rebreathers, often used to allow excess gas and accumulated water in the breathing loop to be vented or in gas supply systems to prevent excessive pressure in the gas feeds to solenoid valves.

Oxidation — A chemical reaction or reactions in which oxygen is added to a substance.

Oxygen cell — See *oxygen sensor* and *galvanic fuel cell sensor*.

Oxygen clean — A state of cleanliness whereby materials/components of a system are suitable for exposure to high-pressure oxygen.

Oxygen compatible — A material that is suitable for use with high-pressure oxygen.

Oxygen consumption (VO_2) — A measure of the rate of oxygen consumption. Resting VO_2 is usually assumed to be 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ (1 metabolic equivalent [MET]). Aerobic capacity ($VO_{2\ max}$) can be described as multiples of 1.0 MET. Recommendations for minimum $VO_{2\ max}$ to be maintained by divers range from a low of >6.0 MET to >13 MET.

Oxygen control system — The components of a rebreather that maintain the concentration of oxygen in the breathing loop. The system usually includes sensors, electronics and a solenoid valve that injects oxygen.

Oxygen-induced myopia — Myopia that is a consequence of excessive oxygen exposure; also known as lenticular oxygen toxicity.

Oxygen rebreather — A type of closed-circuit rebreather that incorporates only oxygen as a gas supply. The earliest form of closed-circuit rebreather, it is most often used for covert military operations, submarine escape and mine rescue operations.

Oxygen sensor — Any sensor that produces a signal related to oxygen pressure or concentration. In diving, the most common type is a galvanic cell that generates an electrical voltage that is proportional in strength to the partial pressure of oxygen exposed to the sensor.

Figure 11. Predive checks using checklists or automated systems are a critical component of rebreather safety. Photo courtesy Jill Heinerth.

Oxygen service — See *oxygen clean*.

Oxygen toxicity — Symptoms experienced by individuals suffering exposures to oxygen that are above normal ranges tolerated by human physiology. See also *pulmonary oxygen toxicity* and *central nervous system oxygen toxicity*.

P

Partial pressure — The portion of the total gas pressure exerted by a single constituent of a gas mixture, calculated by multiplying the fraction of the gas by the absolute pressure of the gas.

Passive addition — Gas-addition systems utilized by some semiclosed-circuit rebreathers to passively inject gas into the breathing loop; usually achieved by a mechanical valve that opens in response to a collapsed bellow or drop in breathing-loop gas pressure.

PCO_2 — The partial pressure of carbon dioxide in a gas mixture, usually referring specifically to the breathing-gas mixture inhaled by a diver.

PN_2 — The partial pressure of nitrogen in a gas mixture, usually referring specifically to the breathing-gas mixture inhaled by a diver.

PO_2 — The partial pressure of oxygen in a gas mixture, usually referring specifically to the breathing-gas mixture inhaled by a diver.

PO_2 setpoint — The PO_2 value that is used by a control system to determine when a solenoid valve injects oxygen into the breathing loop.

Pressure vessel — A container with sufficient structural integrity to safely contain gas at a pressure greater than ambient. Typical diving pressure vessels are manufactured from steel or aluminum alloy and cylindrical in shape but may also be spherical.

psi — A unit of pressure measured in pounds per square inch (1 psi = 55 mmHg = 6.9 kPa).

Pulmonary barotrauma — Damage to the pulmonary alveoli due to changes in pressure, usually as a result of increased internal pressure potentially resulting in air/gas embolism, pneumothorax or emphysema. Potential cause in diving is breathholding during ascent.

Pulmonary function — The factors included in the act of breathing including ventilator mechanics, alveolar ventilation and gas exchange.

Pulmonary oxygen toxicity — Pulmonary irritation typically caused by prolonged exposure to breathing mixtures with oxygen partial pressures in excess of 0.5 ata. This form of oxygen toxicity primarily affects the lungs and causes pain on deep inhalation as well as other symptoms.

Q

Quality assurance (QA) — Methods to prevent mistakes or defects in manufactured products. QA can be applied to physical products in preproduction and postproduction to verify that specifications are met.

R

Radial CO_2 absorbent canister (radial scrubber) — A cylindrical CO_2 absorbent canister design wherein the gas flows laterally from the outside to a hollow tube on the inside (or vice-versa).

Rebreather — Any form of life-support system where the user's exhaled breath is partially or entirely recirculated for subsequent inhalation.

Recompression — Returning to a pressure greater than ambient.

Recompression chamber — An enclosed pressure vessel fit for human occupancy that enables internal pressure to be rapidly increased above ambient. Typically recompression chambers are used to treat decompression sickness. See also *hyperbaric chamber*.

Redundancy — The duplication of critical components or functions in a system with the intention of increasing reliability, usually in the form of a backup system in case of primary system failure.

Figure 12. Open-circuit bailout should be practiced regularly. Photo courtesy Jill Heinerth.

Repetitive dive — A dive whose decompression obligation is influenced by a previous dive or pressure exposure.

Residual nitrogen — The amount of nitrogen remaining in a diver's tissues following a hyperbaric exposure. A similar denotation can be applied to helium or other inert gas.

Respiratory exchange ratio (RER or R) — The ratio between the amount of carbon dioxide expired and the amount of oxygen consumed. RER increases as a function of metabolic rate. Formerly known as respiratory quotient (RQ). It can be estimated that 0.9 L of carbon dioxide will be produced for every liter of oxygen consumed.

Respiratory load — Any load or breathing impediment that makes it harder to breathe. Respiratory loads include breathing resistance, elastic loads and static lung load (hydrostatic imbalance). Elevated inspired CO_2 will make a person breathe more, which increases the effects of other respiratory loads.

Respiratory minute volume (RMV) — The volume of gas inhaled and exhaled during one minute of breathing.

Respiratory quotient (RQ) — See *respiratory exchange ratio*.

S

Safety stops — Stops carried out during ascent that are not required by the decompression model being followed for the dive.

Saturated tissue(s) — The point at which the partial pressure of a gas dissolved in a tissue is equal to the partial pressure of that gas in which it is in contact with.

Saturation — The condition in which the partial pressure of a gas dissolved in a fluid is equal to the partial pressure of that gas in which it is in contact; i.e., the point at which the rate of gas exchange into a fluid matches the rate of gas exchange out of a fluid into the surrounding environment.

Scrubber — See *CO_2 absorbent canister*.

Scuba — Self-contained underwater breathing apparatus.

Semiclosed-circuit rebreather (SCR) — A type of rebreather that injects a mixture of nitrox or mixed gas into a breathing loop to replace that which is used by the diver for metabolism; excess gas is periodically vented into the surrounding water in the form of bubbles.

Sensor validation — Methods to confirm the appropriate function of sensors, typically oxygen sensors.

Setpoint — See *PO_2 setpoint*.

Shoulder port — The connectors in a breathing loop that connect the breathing hoses to the counterlungs mounted over the diver's shoulders, sometimes serving as water traps to divert condensation and leaked water into the counterlungs.

Silent bubbles — Gas bubbles that may be detected in the blood vessels or tissues but that are considered to not result in signs or symptoms of decompression sickness.

Skip breathing — The practice of inhaling, holding the breath and then exhaling slowly to attempt to extend the time underwater by using less air. This practice can lead to buildup of CO_2 (hypercapnia).

Soda lime — A general term referring to a chemical agent that reacts and bonds with CO_2 and is commonly used in the scrubbers of rebreathers.

Solenoid valve — A valve that opens when electricity is applied to an electromagnetic solenoid coil; usually the type of valve used to inject oxygen into the breathing loop of a closed-circuit rebreather.

Solid state sensor — A sensor with no mobile parts that detects or measures a physical property.

Stack time — A term used to describe the predicted time that a canister of CO_2 absorbent will last before it needs to be replaced.

Static lung load (SLL; hydrostatic imbalance) — The pressure gradient between the outside and inside of the chest imposed by underwater breathing apparatus, which can affect diver comfort and respiratory efficiency, especially during exertion. The lungs can be thought of as having a center (lung centroid) located approximately 17 cm below and 7 cm behind the suprasternal notch on the chest. SLL represents the difference between the pressure delivered by the breathing apparatus (at the start of an inspiration) and the pressure at the lung centroid. If gas is delivered to the diver at a pressure equal to the depth of the lung centroid then no SLL is imposed. A person immersed to the neck has pressure inside the chest at atmospheric and outside the chest at the elevated water pressure. This represents negative SLL and can be measured as the depth of the lung centroid. A negative SLL will make a person breathe at smaller lung volumes, while a positive SLL makes a person breathe at larger lung volumes. For scuba diving, the placement of the regulator determines the SLL. A regulator in the mouth of an upright diver imposes a negative SLL. If the vertical diver is head down, then the SLL would be positive. A prone diver may have a slightly positive SLL. A diver swimming shoulder down will not have an SLL imposed. With rebreathers, the placement of rebreathing bags and the amount of gas therein determines SLL. Since gas collects at the top of the bags, the orientation of the diver also matters. The pressure delivered by the breathing apparatus is determined by the depth of the bottom of the gas bubble. The SLL is then equal to the difference between this pressure and the pressure at the lung centroid. A backmounted bag will impose a negative SLL. A chestmounted bag will impose a positive SLL. Over-the-shoulder bags with the right amount of gas in them may have a neutral SLL, but the actual SLL varies with gas volume and can be positive or negative. If a diver with an over-the-shoulder bag rebreather swims with a shoulder down, then the SLL may be negative since the gas will collect in the upper bag; should the gas volume be large enough that all breathing is in the lower bag, then the SLL will be positive. Should the gas volume in the upper bag be such that an exhalation forces some gas into the lower bag, then a sudden large pressure increase is required by the respiratory muscles.

Statistical dependence — A condition in which two variables are not independent, meaning that both variables are potentially subject to the same external factors in similar ways. For example, two oxygen sensors manufactured by the same process and produced in the same production batch are statistically dependent because a failure in the production process could affect both sensors in the same way.

Surface-supplied — A form of diving where gas is supplied from compressors or pressure vessels located at the surface.

Symptoms — Perceptible changes in body state or function that may be indicative of disease or injury.

T

Technical diving — A form of scuba diving that exceeds conventional limits, generally including dives that are deeper than 130 ft (40 m), using mixed gas, requiring multiple cylinders or decompression, or taking place within overhead environments.

Temperature stick — An array of thermal sensors aligned in the CO_2 absorbent canister to monitor the thermal activity of the absorbent material (measuring the advance of the thermal front) to provide information on absorbent depletion. Also known to as a Temstick or thermal profile monitor (TPM).

Thermocline — An abrupt change in water temperature at depth.

Tidal volume (V_T) — The amount of gas ventilated in a respiration cycle. Tidal volume changes as a function of exercise intensity and metabolic requirements.

Trim — A term denoting the balanced buoyancy of a diver in the water. A horizontal trim under a condition of neutral buoyancy results in the optimum trim for underwater swimming.

Trimix — A gas mixture containing three constituents, usually oxygen, nitrogen, and helium.

Tympanic membrane (eardrum) — The membrane separating the external auditory canal from the middle ear.

Type R rebreather — Semiclosed or fully closed electronic rebreather designed for use in recreational diving situations and characterized by ease of use in no-stop diving applications.
Type T rebreather — Rebreather designed for use in technical-diving situations, usually having various manual override options for emergency situations.

U

Unit pulmonary toxicity dose (UPTD) — A unit of measure used for calculating the total oxygen exposure incurred during all phases of a dive or series of dives; typically used to manage pulmonary (whole body) oxygen toxicity exposure.

Upstream — A relative direction with respect to the flow of gas through the breathing loop of a rebreather; the direction of travel of the diver's inhaled gas. See also *downstream*.

Upstream check-valve — A check-valve, typically located near the mouthpiece of a rebreather, that prevents subsequent re-inhalation of exhaled gas by preventing it from traveling in an upstream direction into the inhalation breathing hose and counterlung.

V

Valsalva maneuver — Technique used to equalize the pressure in the middle ear with ambient pressure. Achieved by increasing pressure in the oral chamber against a blocked nose, mouth and glottis.

Vasoconstriction — A decrease in the diameter of blood vessels, especially the smallest arteries (arterioles), resulting in decreased blood flow to a part of the body.

Vasodilation — An increase in the diameter of blood vessels, especially the smallest arteries (arterioles), resulting in increased blood flow to a part of the body. During diving, typically a consequence of hypercapnia.

Ventilate — The act of moving gas in and out of the lungs.

Venting breath — A type of breathing pattern used to purge gas from a breathing loop; accomplished by inhaling through the mouth and exhaling through the nose into the mask or around the edge of the mouthpiece, thus removing gas from the breathing loop.

Vertigo — A disorientating state in which the individual and/or the surroundings appear to rotate.

Vestibular bend — Decompression sickness involving the inner ear.

Vestibular system — The part of the inner ear concerned with balance.

Vital capacity — The maximum volume of gas that can be expelled following a maximum inspiration.

Volume-averaged pressure (aka resistive effort) — Terminology used by the U.S. Navy Experimental Diving Unit (NEDU) to describe work of breathing (WOB) in correct physical units and physiological terms. It is equivalent to the difference between inhalation and exhalation pressures averaged across a diver's breath and is sensitive to flow resistance.

Voting algorithm/logic — The procedure in which rebreather electronics rely upon output from multiple sensors to determine when oxygen needs to be added.

W

Whole-body oxygen toxicity — See *pulmonary oxygen toxicity*.

Workload — A representation of the level of physical exertion; often measured through oxygen consumption in a laboratory setting.

Work of breathing (WOB) — The effort required to complete an inspiration and expiration cycle of breathing. For a breathing apparatus, the work of breathing can be affected by breathing hose diameters, check-valve design, scrubber design, depth, absorbent material, and other factors. The placement of counterlungs does not affect the WOB but is a respiratory load by itself.

SCHEDULE

Friday, 18 May 2012

Time	Event	Moderator/Speaker
Rebreather Forum 3.0 Welcome (Caribbean Ballroom III)		
07:30	Registration/Pool Sign-Up/Exhibition Opens	
08:00	Opening Remarks and Orientation	Drew Richardson
08:15	Anatomy of a CCR Dive: Contrast and Comparison	Simon Mitchell
Rebreather Explorer Day (Boca Room II)		
09:00	Pool Session Opens	
09:15	Diving with Rebreathers	Richard Pyle
09:45	Why I Stopped Blowing Bubbles	James Morgan
10:15	Failure Is NOT an Option: Importance of Checklists	Richie Kohler
10:45	Break/Pool Sign-Up	
11:00	The Envelope Opener	Martin Robson
11:30	The Five Golden Rules	Jill Heinerth
12:00	Getting Closer to the Action with CCRs	Evan Kovacs
12:30	Lunch	
13:00	The Six Skills	Steve Lewis
13:30	Heart of Darkness	Phil Short
14:00	And Don't Get It Wet…	Bruce Partridge
14:30	Pool Diving Ends/Exhibition Closes/Break	
CCR Medicine and Physiology (Boca Room III)		
09:15	Thermal Physiology and Protection	Neal Pollock
10:15	Break	
10:30	Open- and Closed-Circuit Diving Fatalities	Petar Denoble, Dan Orr
11:30	Decompression Methods	David Doolette
12:30	Lunch	
13:30	CCR Physiology	Simon Mitchell
14:30	Pool Diving Ends/Exhibition Closes/Break	
CCR Business and Operations (Boca Room IV)		
09:15	CCR Business Panel	Mark Caney
10:15	Break	
10:30	CCR Travel Panel	Nancy Easterbrook
11:30	20 Years of CCR Training Data by ANDI, IANTD, TDI	Ed Betts, Brian Carney, Joe Dituri
12:30	Lunch	
13:30	U.S. Coast Guard Role in Investigations	LT Jed Raskie, USCG
14:30	Pool Diving Ends/Exhibition Closes/Break	
RF3 Introductory Sessions (Caribbean Ballroom III)		
15:00	Rebreather Forum 3.0 Orientation	Drew Richardson
15:15	Lessons Learned from Rebreather Forum 2	Michael Menduno
16:15	Rebreather Education and Safety Association Mission	Jerry Whatley
16:30	Rebreathers: Overcoming Obstacles in Exploration	Richard Harris
17:20	CCR Communities	Martin Robson
	Military	CDR Mike Runkle, USN Supv of Diving
	Scientific	Christian McDonald
	Media	Evan Kovacs
	Recreational	Mark Caney
	Technical	Phil Short
	Cave	Lamar Hires
19:10	Loud Shirt Party	

Saturday, 19 May 2012

Time	Event	Moderator/Speaker
Focus Zone 1 — CCR Incidents		Petar Denoble
08:00	CCR Diving Fatalities Review (10-minute discussion)	Andrew Fock
09:10	Accident Investigation (10-minute discussion)	David Concannon
10:20	Break	
10:40	Hazard Analysis and Human Factors (10-minute discussion)	Bill Stone
11:50	Lunch/Exhibition Open	
Focus Zone 2 — Design and Testing (Part I)		John Clarke
13:15	Real-Time Monitoring (10-minute discussion)	Martin Parker
14:15	O_2 Sensors	Arne Sieber
15:05	Break/Exhibition Open	
15:25	CO_2 Sensors (10-minute discussion)	Kevin Gurr
16:25	CO_2 Scrubber Technology (10-minute discussion)	Dan Warkander
17:25	Information Technology (10-minute discussion)	Bruce Partridge
18:25	Break/Exhibition Open	
19:15	Drinks Reception	
20:00	Rebreather Forum 3 Gala Dinner and Lecture "Exploration: From Sea to Space and Back"	Michael Gernhardt

Sunday, 20 May 2012

Time	Event	Moderator/Speaker
Focus Zone 2 — Design and Testing (Part II)		John Clarke
08:00	O_2 Control	Nigel Jones
08:40	Premarket Testing (10-minute discussion)	Mike Ward, Gavin Anthony
09:40	Break/Exhibition Open	
10:00	Post-Incident Testing (10-minute discussion)	Oskar Franberg, John Clarke, Vince Ferris
11:00	Semiclosed Systems	John Clarke
11:40	Lunch/Exhibition Open	
Focus Zone 3 — Operations and Training		Phil Short
12:40	Operations (10-minute discussion)	Jeff Bozanic
14:10	Break	
14:30	Training (10-minute discussion)	Jill Heinerth, Terrence Tysall
16:00	Break/Exhibition Open	
16:30	Recommendations, Findings and Discussion	Simon Mitchell
18:30	Closing Remarks	Drew Richardson

Organizational Acronyms

AAUS — American Academy of Underwater Science
ANDI — American Nitrox Divers International
CMAS — Confédération Mondials Des Activités Subaquatiques
DAN — Divers Alert Network
FBI — Federal Bureau of Investigation
IANTD — International Association of Nitrox and Technical Divers
NASA — National Aeronautics and Space Administration
NAUI — National Association of Underwater Instructors
NAVEODTECHDIV — Naval Explosive Ordnance Disposal Technology Division
NPS — National Park Service
NOAA — National Oceanic and Atmospheric Administration
PADI EMEA — Professional Association of Diving Instructors, Europe, Middle East & Africa
RAID — Rebreather Association of International Divers
SAA — Sub Aqua Association
SSI — Scuba Schools International
TDI / SDI / ERDI — Technical Diving International / Scuba Diving International / Emergency Rescue Diving International

RF3 Attendee List

Terence Adams
US Navy
Panama City, Florida, USA

Matthew Addison
Hollis
San Leandro, California, USA

Nicolas Alvarado-Quiroz
NOAA
St. Petersburg, Florida, USA

Mike Ange
SSI
Fort Collins, Colorado, USA

Joe Angelo
Neal Group
Key Largo, Florida, USA

Gavin Anthony
QinetiQ
Farnborough, Hampshire
United Kingdom

Dawn Azua
PADI Worldwide
Rancho Santa Margarita, California, USA

Nick Bailey
Health & Safety Laboratory
Bakewell, Derbyshire
United Kingdom

Vikki Batten
PADI EMEA
Bristol, North Somerset
United Kingdom

Rikki Battistini
Battistinis Custom Cycles
Irvine, California, USA

William Bedford
Bristol Myers Squibb
Media, Pennsylvania, USA

Doug Bell
Scuba North
Traverse City, Michigan, USA

Marcus Benér
Poseidon
Gothenburg, Sweden

Ronald Benson
Silent Explorers
Maple Grove, Minnesota, USA

Fredi Berger
IDC Scuba
Newport, Victoria
Australia

Josh Bernstein
Advanced Diver Magazine /
Rebreather World Forum
Bradenton, Florida, USA

Michael Berumen
King Abdullah University
of Science and Technology
Thuwal, Saudi Arabia

Edward Betts
ANDI
Freeport, New York, USA

Nicholas Bird
DAN
Durham, North Carolina, USA

Jason Blackwell
Dive Dive Dive
Wakerley, Queensland
Australia

Dale Bletso
Airheads Dive Ops
Brooks, Kentucky, USA

Marc Blouin
US Geological Survey
St. Petersburg, Florida, USA

David Boaz
St. Thomas
U.S. Virgin Islands

Stephen Bohan
Navair
Orlando, Florida, USA

Nick Bostic
Leisure Pro
New York, New York, USA

Curt Bowen
Advanced Diver Magazine /
Rebreather World Forum
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Jeff Bozanic
Next Generation Services
Huntington Beach, California, USA

Jonas Brant
Poseidon
Gothenburg, Sweden

Lucio Bravin
Scuba Du
Brasilia, Brazil

John Bright
National Park Service / Submerged
Resources Center
Lakewood, Colorado, USA

Peter Broger
Cave Training Mexico
Milan, Italy

Chris Brown
Silent World
Key Largo, Florida, USA

John Brumm
Bonnier Corp / Sport Diver
Magazine
Winter Park, Florida, USA

Andy Brunton
Divex
Portsmouth, Hampshire
United Kingdom

Michael Bryant
Sandy Bottom Scuba
Arlington, Virginia, USA

Alex Brylske
Dive Training Magazine
Summerland Key, Florida, USA

Les Burke Jr
Scientists in the Sea
Woodbridge, Virginia, USA

Dave Burroughs
Hollis
San Leandro, California, USA

Alexander Busch
Draeger Safety AG & Co
Luebeck, Germany

Josh Butner
Apeks Aqua Lung
Vista, California, USA

Zachary Caldwell
The Nature Conservancy
Honolulu, Hawaii, USA

Robert Camus
Scuba Ventures
Shreveport, Louisiana, USA

Mark Caney
PADI EMEA
Bristol, North Somerset
United Kingdom

Glen Caristinos
Tampa, Florida, USA

Brian Carney
TDI / SDI / ERDI
Jensen Beach, Florida, USA

Tony Cerezo
Puerto Rico Technical Diving Center
Aguadilla, Puerto Rico

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