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The value of closed-circuit rebreathers for biological research

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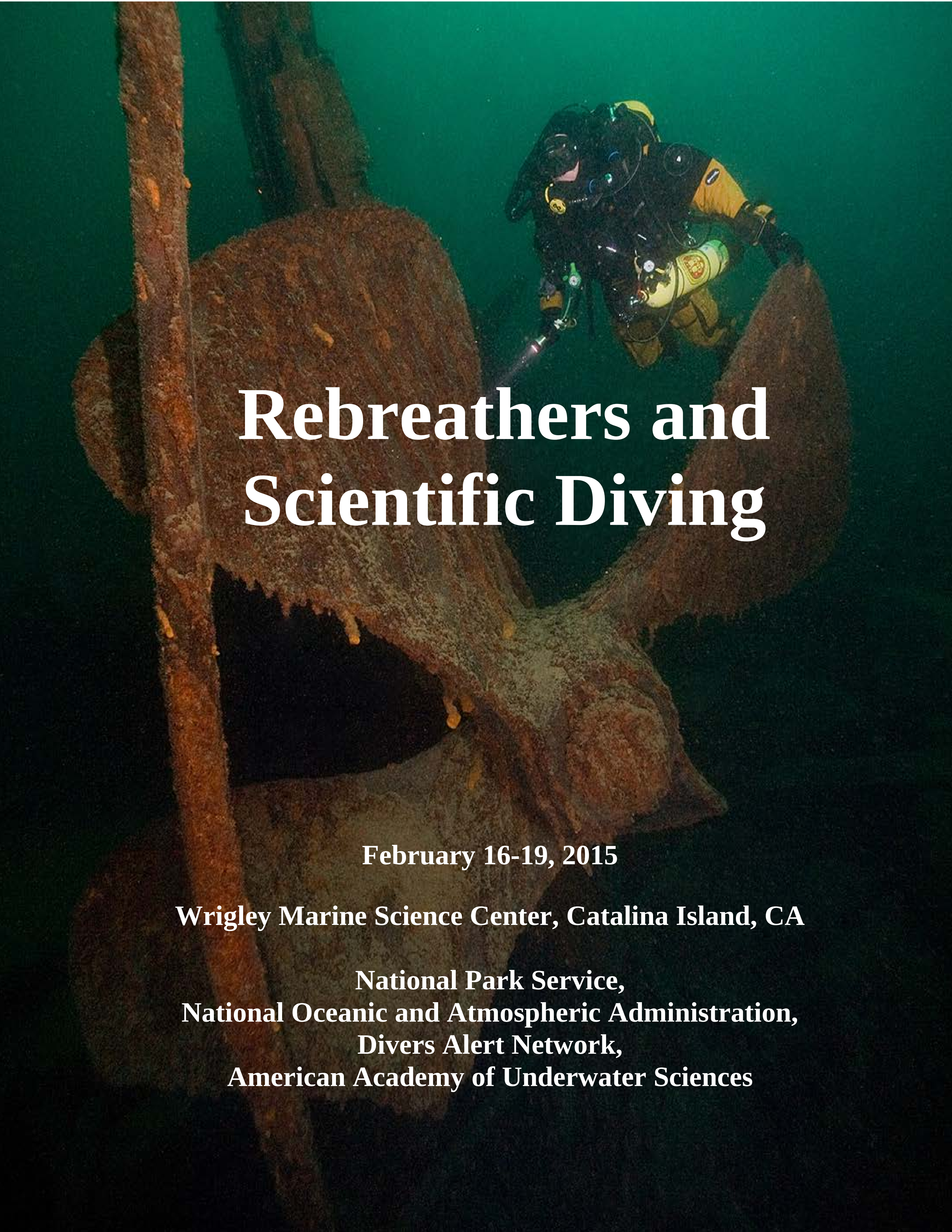

Rebreathers and Scientific Diving

February 16-19, 2015

Wrigley Marine Science Center, Catalina Island, CA

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American Academy of Underwater Sciences

Rebreathers and Scientific Diving

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The Value of Closed-Circuit Rebreathers for Biological Research

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Abstract

Closed-circuit rebreathers have been used for underwater biological research since the late 1960s, but have only started to gain broader application within scientific diving organizations within the past two decades. Rebreathers offer certain specific advantages for such research, especially for research involving behavior and surveys that depend on unobtrusive observers or for a stealthy approach to wildlife for capture and tagging, research that benefits from extended durations underwater, and operations requiring access to relatively deep (>50 m) environments (especially in remote locations). Although many institutions have been slow to adopt rebreather technology within their diving programs, recent developments in rebreather technology that improve safety, standardize training requirements, and reduce costs of equipment and maintenance, will likely result in a trend of increasing utilization of rebreathers for underwater biological research.

Keywords: biology, rebreather, field operations

Introduction

Although modern rebreathers were originally developed in 1878, they were used primarily for military and commercial purpose for most of the ensuing century (Davis 1955; Quick 1970). Among the earliest use of rebreathers for science was that of Walter Starck, who invented the first electronically-controlled closed-circuit rebreather (CCR) primarily for use in undersea biological research (Tzimoulis 1970; Starck and Starck 1972). Soon thereafter, rebreathers were used during the TEKTITE II project (Collette and Earle 1972) to conduct biological research during excursions from an undersea habitat, and to observe squid behavior (Hanlon et al. 1982). By the mid-1980s, a renewed interest in rebreathers for scientific cave exploration coincided with the dawn of what has come to be known as "Technical Diving" (Stone 1989; Stone 1990; Hamilton 1990). At around the same time, underwater film-makers Howard Hall and Bob Cranston began using closed-circuit rebreathers to more effectively approach marine life underwater (Hall 1990). By the mid- to late-1990s, rebreathers became increasingly available from several manufacturers, and gradually started to be used by the scientific diving community, including for biological research in remote locations (e.g., Pyle 1996; Pyle 1998; Pyle 1999; Lobel 2001; Pence and Pyle 2002; Parrish and Pyle 2002; Tomoleoni et al. 2012). As more scientific diving organizations incorporate rebreathers into their programs (Kintzing and Slattery 2016), they will become an increasingly important tool for conducting biological field research.

Rebreathers for Biological Research

The advantages and disadvantages of closed-circuit rebreathers in general (see various chapters in Vann et al. 2014) apply to scientific diving in the same way that they apply to any rebreather diving. There are no disadvantages that are particular to biological research; but there are a number of specific advantages of rebreather diving over conventional or mixed-gas scuba diving that apply to underwater scientific operations in general, and biological research in particular (Sieber and Pyle 2010). These specific advantages include quieter, less obtrusive underwater intervention, extended underwater durations, and more practical operations in deep water, particularly in remote locations.

Stealth

Perhaps the most obvious advantage of closed-circuit rebreathers for biological research is the absence of bubbles produced during each exhaled breath during an open-circuit scuba dive (Lobel 2001; 2005; Schmidt and Gassner 2006; Dickens et al. 2011). Not only do such bubbles produce a loud gurgling noise, but the sudden appearance of a tumultuous silver cloud may also be visually disturbing to marine life (Sharpe and Dill 1997). Any research that involves observations of natural behavior in aquatic life could potentially benefit from the reduction of noise and visual disturbance characteristic of open-circuit scuba.

During the TEKTITE missions of 1969, Bright (1972) noted the benefit of the noiseless rebreather when recording fish behavior. Hanlon et al. (1982) evaluated the advantages of rebreathers for underwater observations of cephalopods and fishes at moderate depths, and concluded that their use offers "...a distinct advantage in collecting behavioral data." Similar observations concerning the response of schooling hammerhead sharks and other large marine life were noted by Hall (1990). The first author (Pyle) and collaborators have made many anecdotal observations while using closed-circuit rebreathers that suggest a dramatic difference in the behavior of marine life, compared with open-circuit scuba dives. Three examples are worth reporting in some detail.

The first case involved Pyle's first ocean dive on a closed-circuit rebreather in 1994. He and his dive partner John L. Earle made a shallow dive at a site known as "Electric Beach" at Kahe Point on the west side of Oahu, Hawaiian Islands. Soon into the dive, they encountered a group of 16 sandbar sharks swimming slowly around the reef. The divers had never seen such an aggregation of sharks at this site despite hundreds of previous open-circuit dives. The sharks were not aggressive, and swam in very close proximity to both divers. At one point during the dive, Pyle switched his rebreather mouthpiece to open-circuit mode, and the sharks gradually dissipated over the course of a few minutes, until none could be seen. He then switched back to closed-circuit mode, and the sharks returned and remained for the duration of the closed-circuit dive.

Another case involved a large aggregation of surgeonfishes at an isolated reef outcrop at a depth of 80 fsw (25 msw) off south Oahu in the Hawaiian Islands. On multiple occasions, small groups of 8-10 individuals were observed to break away from the large aggregation to swim rapidly across the open sand to a large rock located approximately 50 ft (15 m) away from the reef. Each group released gametes directly above the rock, then immediately returned to the large aggregation. As he was observing this behavior, Pyle speculated that the fishes may be taking advantage of turbulence above the rock as the current flowed across the reef to assist in mixing the gametes after spawning. Just as he was contemplating the reason for this behavior, a group of 8-10 surgeonfishes broke away from the large aggregation and swam out across the sand toward him, and released their gametes directly above his head. Evidently, the fish had mistaken Pyle (who was kneeling motionless in the sand) as another rock.

In 2002, while Pyle and John Earle were decompressing from a deep dive on a shallow reef in Fiji, they encountered a group of about twenty reef squid. The squid were interacting with each other in multiple ways, with males and females copulating in mid-water, females laying eggs deep within the reef structure, and males apparently guarding females and aggressively attacking other males. Pyle and Earle observed this activity at very close range for an extended period, capturing the behaviors on video (Figure 1). The squid were so oblivious to the presence of the divers, that at one point a squid literally bumped into the lens port on the video camera, without any apparent change in behavior. After observing this scene for about twenty minutes, the group of squid inexplicably swam away from the reef. Less than a minute later, a diver using open-circuit scuba swam by. As soon as the open-circuit diver had moved off, the squid returned to resume their behavior. Just at that moment, a small jack attacked the squid resulting in clouds of ink, and the squid swam off again. Thus, the rebreather divers were able to observe and document both spawning and predation behaviors that would very likely not be seen by a diver using open-circuit scuba.

Figure 1. John L. Earle observing spawning of reef squid in Fiji.
Frame from a video recorded by R.L. Pyle.

Although many such anecdotal observations underscore the qualitative advantages of closed-circuit rebreathers compared with open-circuit scuba, there are also more quantitative differences as well. In particular, research involving quantitative surveys of marine life may be improved through the use of closed-circuit rebreathers. Collette (1996), in extoling the virtues of rebreathers for biological research, wrote, "I question the validity of all fish behavioral studies done with scuba because of the demonstrated disturbing effects of the noisy bubbles." Lobel (2001) also noted the distinctly different and more inquisitive behavioral reactions of juvenile parrotfish, eels and grey reef sharks when using a rebreather. Cole et al. (2007) compared results from fish surveys using both rebreathers and open-circuit scuba, and concluded that, "for the species and sampling methods examined, semi-closed [rebreathers] did not offer sufficient practical advantages or produce density estimates that were sufficiently distinct from [open-circuit scuba] to warrant the extra expense and training." However, this study involved semi-closed rebreathers, which produce some bubbles during normal operation. In a much more exhaustive study, Lindfield et al. (2014) compared data from fish transects for closed-circuit and open-circuit scuba, and concluded, "The use of CCR for fish surveys clearly minimizes behavioral biases associated with fish avoiding open-circuit scuba divers. We recommend the use of this bubble-free diving system for surveys assessing reef fish populations, especially in areas where fish are heavily targeted by spearfishing. If fish behavior is not accounted for, surveys using scuba could result in erroneous conclusions when comparing fished and protected areas."

Figure 2: A team of USGS sea otter capture divers stage for a dive in the shallow waters of the Alaska Peninsula. Here, divers are using both front-mounted Draeger LAR V (foreground) and back-mounted Aqualung FROGS (background) oxygen rebreathers. Photo: USGS.

Closed-circuit oxygen rebreathers have been used by biologists at the United States Geological Survey (USGS), California Department of Fish & Wildlife (CDFW), University of California Santa Cruz, and US Fish & Wildlife Service to capture wild sea otters (*Enhydra lutris*) since 1988 (Tomoleoni et al. 2012; Sanders and Wendell 1991; Figure 2). Sea otters must be captured periodically to conduct health assessments, tag, or translocate individual animals. Sea otter capture divers use a net-lined basket called a Wilson Trap attached to the nose of a modified diver propulsion vehicle to catch the otters (Figure 3). The divers ascend from directly below the otters and envelop them in the trap. These capture dives were initially performed using conventional open-circuit scuba with limited success. In order to successfully capture a sea otter, the dive team must avoid detection by operating in a stealth mode similar to military divers. In the early days, the exhaled bubbles inherent to open-circuit systems frequently gave away the location of the dive team and prevented the divers from positioning directly under the target otters. This commonly resulted in the target sea otters swimming away before the divers could get close. Switching to a closed-circuit rebreather rig eliminated the bubble problem. On rebreathers, the divers could navigate a course to the target otters and even hover directly below a sea otter, inches away, and remain completely undetected.

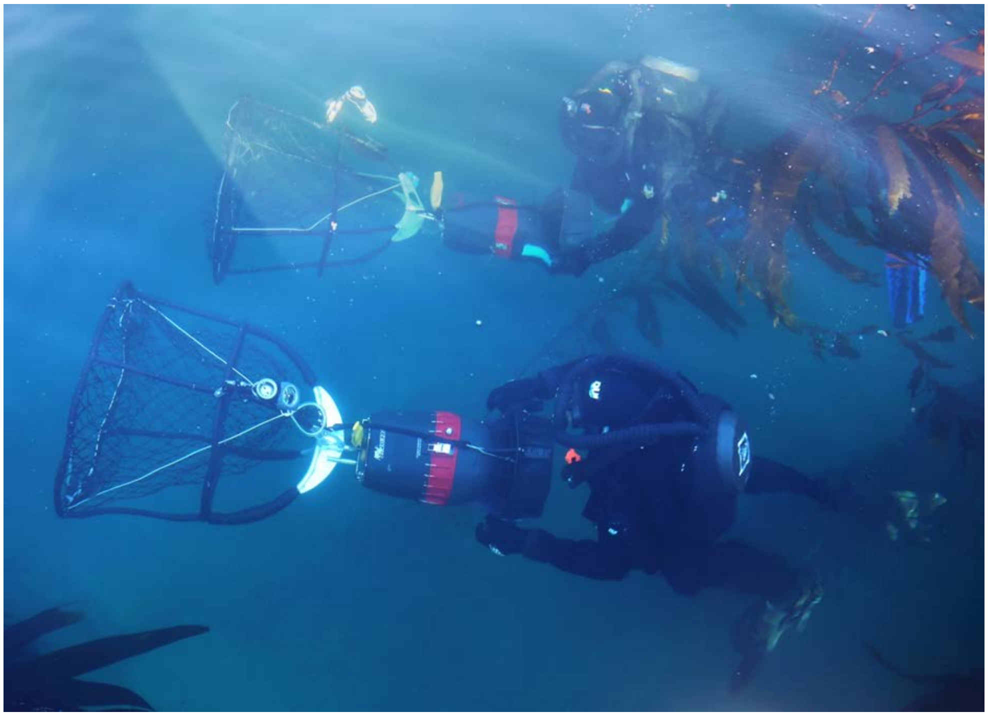

Figure 3: A USGS sea otter capture dive team, using Carleton COBRA oxygen rebreathers, begins a capture dive. Photo: David Osorio, CDFW.

Rebreathers have become an indispensable tool for the sea otter capture team, particularly in cases where it was necessary to recapture specific individuals. In these recapture situations, the divers often need to position themselves directly under a group of otters for long periods of time while trying to discern which otter is the actual recapture target. This was a nearly impossible task on open-circuit scuba, but the bubble-less closed-circuit divers can now remain under the otters for as long as required to identify the correct target animal. Since sea otter capture divers only need to stay deep enough to remain concealed by the surface of the water, or to traverse below a thick kelp forest canopy, dives typically average depths of 6-12 ft (2-4 m) and never more than 20 ft (6 m). The shallow operating depth and need for a "bubble-free" breathing apparatus makes the use of closed-circuit oxygen rebreathers the ideal platform for sea otter capture divers. Capture success rates and efficiency were dramatically improved once divers started using rebreathers. Numerous studies and publications were made possible by the application of this technology, which is essential for the recovery of high-resolution archival data recorders from individual sea otters (Bodkin et al. 2004; Bodkin et al. 2007; Tinker et al. 2007).

The dramatically reduced noise afforded by rebreathers also provides important advantages for biological research involving acoustical recordings. Collette (1996) reported that, during the TEKTITE II project in the early 1970s, "Use of rebreathers greatly facilitated recording fish sounds without the noise produced by the bubbles from open-circuit scuba systems." Lobel (2009) noted, "The use of a closed-circuit (i.e., bubble-free) Rebreathers not only increases the efficiency of the dive time spent making underwater acoustic recordings but also alleviates a significant source of disturbance to the fishes being observed. Furthermore, rebreathers facilitate more rapid habituation of fish to a diver's presence while also extending the bottom-time available for underwater study. The point is that we are learning that the excessive noises of open-circuit scuba can be a disturbance and may also mask biologically important animal sounds." Bubbles not only produce noise but also create near-field vibrations in the water. This water disturbance is probably similar to the hydrodynamic disturbance produced by other swimming fishes such as fast moving predators and can cause the "startle response" (Lobel 2001). Fishes are especially sensitive to such disturbances that are perceived by means of their lateral-line and other sensory pore organs (Fay and Popper 1999; Popper and Fay 1999). Rebreathers are especially useful when recording the behavior and sounds of spawning fishes, which are extremely aware and sensitive to potential predators and open circuit divers around them during reproduction (e.g. Lobel 1978; Lobel 2001; Lobel 2003; Lobel 2005; Tricas and Boyle 2014).

Duration

Another important advantage of closed-circuit rebreathers for biological research is that they provide extended underwater durations, compared with open-circuit scuba. Collette (1996) noted, "Rebreathers are more expensive, but if one can accomplish twice the work in a given unit of time and carry out investigations that take more bottom time than is available with scuba, is it really more expensive?"

There are two aspects of rebreathers that allow extended-duration diving. First, rebreathers are much more efficient with respect to gas consumption, so the duration of any single dive is usually limited by the duration of the CO_2 absorbent, rather than the available gas supplies. The absorbent duration depends on diver metabolic rate and water temperature, and most rebreather absorbent canisters are capable of supporting dive durations of two to three hours in cold water with high exertion, and much longer dives in warm water with low exertion. Second, because most rebreathers maintain a constant oxygen partial pressure (rather than the constant oxygen fraction of open-circuit scuba), decompression characteristics of a dive can be optimized. This allows for greatly extended no-decompression bottom times (especially for multi-level diving), and dramatically reduced decompression times for dive profiles that require some decompression (Sieber and Pyle 2010).

Traditionally, when research divers require extended underwater durations, they rely on conducting multiple consecutive open-circuit scuba dives on a single day. This approach to extending effective bottom times is inefficient, limiting, and potentially unsafe. It is inefficient because substantial time is spent between dives away from productive working time gathering equipment, returning to the boat or shore, ascending (with safety decompression stops), exiting the water, changing out cylinders, and starting a new dive. It is limiting in the sense that projects that require continuous *in-situ* monitoring, or travelling for extended distances (without returning to a boat or shore) cannot easily be accomplished with multiple consecutive short-duration dives. It is potentially unsafe because in many situations, the most potentially hazardous part of the dive is the ascent phase; both for physiological reasons (decompression physiology and potential for barotrauma), and because of the risk of collision with boats or hazardous shore-based entry and exit situations. Another option to extend the duration of open-circuit scuba dives is to use additional cylinders on a single dives, but this increases the complexity of the dives and the total bulk of equipment required, and at best allows for double the duration of a standard single-cylinder open-circuit scuba dive.

Rebreathers avoid these problems by allowing divers to conduct a single, long-duration dive without the need to return to the surface or shore between multiple dives. One example of a project that has benefited from extended-duration diving with rebreathers is research and control of crown-of-thorns starfish (COTS) from shallow reefs in American Samoa. Research divers must survey large expanses of coral-reef habitat in relatively shallow water to monitor the abundance of COTS at different reefs. This project also involves the control of COTS populations by divers injecting ox bile (Chen 2014), which is likewise greatly facilitated by the extended-duration dives afforded by closed-circuit rebreathers (Figure 4).

Figure 4. Kelley Gleason injecting ox bile into a crown-of-thorns starfish in American Samoa while diving with a closed-circuit rebreather. Photo: Greg McFall.

Another research project that has benefited by the extended durations of closed-circuit rebreathers is a multidisciplinary investigation of *Halimeda* algae meadows in Hawaii. The project involved a team of divers conducting surveys of large areas off Maui to examine different aspects of *Halimeda* meadow ecology, such as growth and densities of the *Halimeda* and associated organisms, as well as recording environmental data (Figure 5). The dives were conducted from shore and included surveys at 130 ft, 100 ft, 66 ft and 33 ft (40 m, 30 m, 20 m and 10 m) depth increments, all of which were in the same general region. What would have required multiple dives over several days with open-circuit scuba, could be achieved within a single four-hour multi-level dive using closed-circuit rebreathers.

Figure 5. Heather Spalding conducting research on *Halimeda* meadows off Maui. Photo: David F. Pence.

While optimized decompression with rebreathers is certainly important for deep, mixed-gas dives involving extended decompression times (see next section), it confers particular advantages to dives to more moderate depths (Pyle 1999). Seymore (2012) noted, "We found the 'sweet spot' for [rebreather] diving to range from 50 to 100 feet [15-30 m]." At depths in the range of 20-30 m, the optimized gas mixtures provided by rebreathers that maintain a constant oxygen partial pressure allow for bottom times of several hours or more, with little or no required decompression time. While some of these benefits can be achieved using enriched air nitrox (EAN) on open-circuit dives, such mixtures are optimized for only one depth; which might not represent the actual depth at which research is conducted. The advantage of rebreathers is that the gas mixture is optimized at all depths, which makes them particularly effective for conducting multi-level dives. An example of this advantage is illustrated by a dive conducted by the first author (Pyle) on a shipwreck off south Oahu in Hawaii. After spending nearly an hour near the bottom of the wreck at a depth of about 100 ft (30 m), several minutes of decompression time was required. This decompression time cleared after spending a few minutes on the bridge of the wreck, at a depth of 50 ft (15 m). After another hour spent on the deck of the wreck at about 66-82 ft (20-25 m), a similar small decompression requirement had accrued. Again, this cleared after a few minutes spent at the bridge of the wreck, allowing for even more time on the deck. When the dive finally ended after two and a half hours, there was no decompression requirement. During that dive, two separate teams of open-circuit scuba divers visited the wreck, remaining for only 20 minutes each.

Depth

The advantages of closed-circuit rebreathers for biological research in deep (>60 m) environments are very well documented (Pyle 1998; Pyle 1999; Pyle 2000; Parrish and Pyle 2001; Parrish and Pyle 2002; Pence and Pyle 2002; Sherman et al. 2009; Sieber and Pyle 2010; Rowley 2014; Harris 2014). In particular, they have been used to gain access to deep coral-reef environments to document biodiversity and ecology of these poorly-known ecosystems. This work has led to the discovery of more than a hundred new species of fishes, and dozens of new invertebrates (Pyle 1998; Pyle 2000; Rowley 2014), as well as more quantitative evaluations of coral-reef communities inhabiting such depths than have been possible using alternate forms of investigation (such as mixed-gas open-circuit scuba, remotely operated vehicles and deep-sea submersibles). Indeed, the advent of modern rebreather technology has been a major force in driving the growing interest in exploring and documenting mesophotic coral ecosystems (Hinderstein et al. 2010).

Remote sampling methods to conduct biological research in deeper habitats (e.g., traps, trawls, drop-cameras, and remotely operated vehicles) are generally far less effective than human divers; particularly in complex ecosystems such as coral-reef environments. Deep-sea research submersibles allow direct access to deep environments, but cost tens of thousands of dollars per day to operate and are limited to a few geographic regions where such submersibles are in active use. Moreover, they are also limited in their ability to explore, sample, and document complex coral-reef ecosystems (Figure 6). Because of this, submersibles are most effective for biological research when operating at depths below those accessible by mixed-gas divers (>500 ft [150 m]).

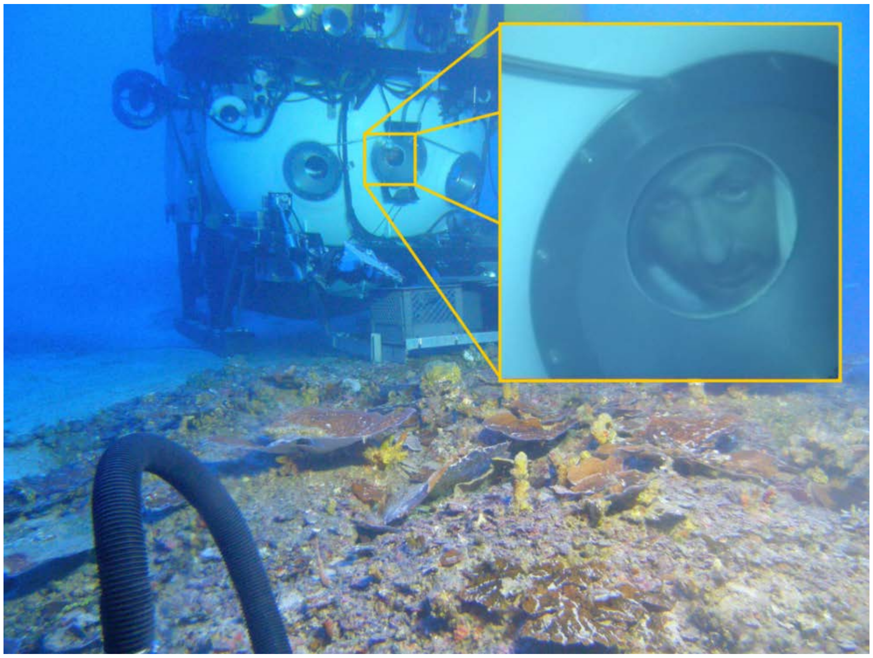

Figure 6. Deep-sea submersibles isolate the researcher from the study environment. Photo: Hawaii Undersea Research Laboratory.

Compared with mixed-gas open-circuit scuba, the main advantages of rebreathers for use on deep diving operations include reduced equipment bulk, greater margins for error (in terms of available breathing gas supplies), and reduced costs of supplies. Rebreather divers still must maintain access to emergency bailout gas supplies, which constitute the majority of total equipment bulk for any deep mixed-gas diving. However, because a rebreather can provide hours of life-support at any depth (compared to minutes for mixed-gas open-circuit systems), the increased margin for error in terms of solving unexpected problems and effecting safe emergency response are greatly increased. Moreover, in more than two decades of deep rebreather diving, the first author has never needed to effect a complete open-circuit bailout, and on only three occasions relied on open-circuit bailout for a temporary bailout (until the rebreather function could be restored). As rebreather systems continue to improve in terms of reliability (Stone 2014), and as closed-circuit bailout options become increasingly available in the future (Pyle 2016), the reliance on open-circuit bailout (and its associated bulk of equipment) will continue to diminish, and the relative advantages of closed-circuit rebreathers compared with open-circuit mixed-gas scuba for biological research in deep environments will continue to increase.

The cost of supplies for deep-diving operations involving closed-circuit rebreathers on deep dives is considerably lower than for open-circuit mixed-gas scuba. A detailed comparison of closed-circuit and open-circuit deep dives revealed that, even taking into account extra costs associated with rebreathers (such as CO_2 absorbent material), supplies for open-circuit mixed-gas divers were nearly five times greater than for identical dives conducted by divers using closed-circuit rebreathers (Parrish and Pyle 2001; Parrish and Pyle 2002). Most of this difference in cost is related to the use of helium. A series of National Oceanic and Atmospheric Administration (NOAA) expeditions involving a team of open-circuit mixed-gas divers required as much as 10,000 cubic feet of helium per expedition (Figure 7). A subsequent comparable expedition that involved closed-circuit rebreather diving required only about 5-10% as much helium to complete a similar number of dives.

Figure 7. Raymond Boland stands next to the helium and oxygen supplies needed for a single NOAA cruise involving open-circuit mixed-gas diving. Photo: Richard L. Pyle.

Remote Field Operations

The majority of biological research conducted by the first author has taken place in remote locations throughout the Pacific (Figure 8). Most of the advantages of rebreathers for biological research described previously also apply to remote field operations. However, by their nature, remote field operations emphasize two aspects of scientific operations more acutely than similar operations that are not as remote: 1) the cost of transporting gear and supplies to remote locations; and 2) the increased value of researcher time during expeditions. The use of rebreathers can greatly reduce the former and increase the efficiency and effectiveness of the latter, compared to open-circuit mixed-gas scuba (Harris 2014).

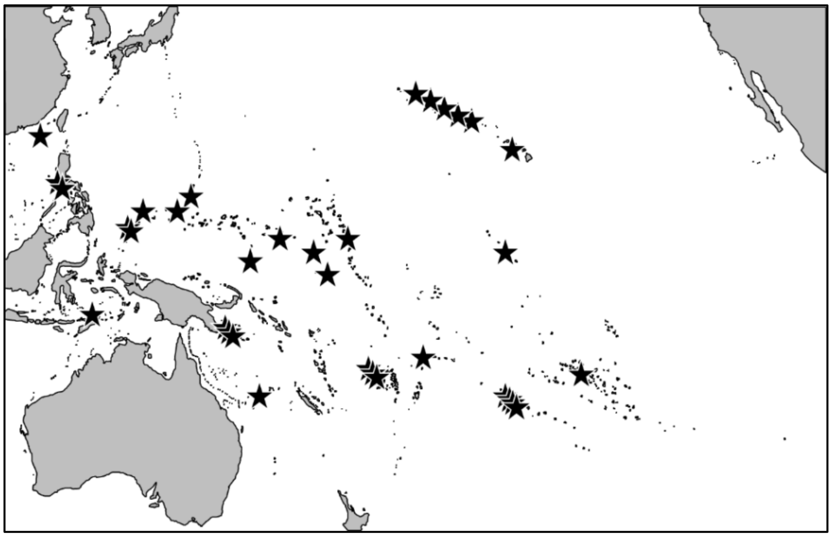

Figure 8. Map of locations where remote field operations involving closed-circuit rebreathers have been conducted by R.L. Pyle and colleagues.

For deep-diving operations involving helium, the advantages of rebreathers are greatly increased in the context of remote locations. The cost of helium increases substantially the farther one gets from major industrial centers. For example, a single cylinder of helium, which would cost less than $100 in a major city within the U.S., may cost upwards of $1,000 (especially when shipping costs are taken into account). This effectively increases the cost-advantage of rebreathers nearly ten-fold (i.e., nearly fifty times less expensive compared with open-circuit mixed-gas scuba, rather than nearly five times less expensive in an industrial location like Hawaii). Also, the mass of equipment needed to conduct deep rebreather dives is substantially less (even when taking into account gear required for bailout purposes) than for comparable operations involving open-circuit mixed-gas scuba, so costs associated with excess baggage and/or cargo shipments can be likewise reduced.

Even more important than transport costs of equipment and supplies is the value of researcher time in the field. Every minute of a researcher's time in remote field locations is precious. Besides the actual dives, data and specimens must be processed each day. Often in remote field operations, the logistical infrastructure and personnel to support deep-diving operations is drastically reduced, so often times the divers and researchers themselves must participate in activities such as gear preparation and gas filling. The aforementioned comparison of open-circuit and closed-circuit mixed-gas diving (Parrish and Pyle 2001; Parrish and Pyle 2002) found that open-circuit dive operations require about two and a half times more support time per productive research time than closed-circuit operations. This takes into account time required for equipment preparation and maintenance, gas filling, and improved decompression efficiency (Table 1).

Table 1. Comparison of time required for support to productive bottom time for open-circuit and closed-circuit diving operations (from Parrish and Pyle 2002)

Activity	Open-Circuit Support Minutes[1]	Closed-Circuit Support Minutes[1]
Preparation & Maintenance	2.25	0.98
Gas Filling	2.53	0.22
Decompression	2.29	1.60
Total	7.07	2.80

1. Per minute of productive bottom time.

These advantages of rebreathers for remote field operations are not limited to deep diving. For example, Seymore (2012) reported a 38% increase in overall productivity after switching to rebreathers, and noted: "With the use of RBs, project logistics have decreased and research time has increased, i.e., we are more productive and efficient in the field. The greatest benefit of [rebreathers] to [the National Park Service] is in the shallower (<130 ft [40 m]) range due to decreased decompression and increased repetitive dive times. Our time conducting in-water work in remote and inaccessible places has increased significantly."

Conclusions

As one of the earliest adopters of closed-circuit rebreathers for biological research, Collette (1996) lamented, "I am amazed and greatly disappointed at the failure to replace standard open circuit scuba with rebreathers." Indeed, the scientific diving community has been slow to adopt closed-circuit rebreather technology. This is a result of several factors, including increased cost and training requirements, as well as more involved maintenance procedures compared with open-circuit scuba. Moreover, there is some evidence to suggest that rebreather diving carries an increased level of risk (Fock 2014). However, McDonald and Lang (2014) noted, "Broader integration of rebreathers [into the scientific diving community] 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."

Indeed, as equipment and maintenance costs for rebreathers continue to fall, and training programs are both simplified and standardized, it is likely that use of rebreathers will increase among underwater biological researchers. While the advantages of stealth and safer access to deep-water environments have been the primary motivators for early adopters of rebreathers in biological research, these advantages apply to only a small fraction of underwater biological research projects. The most significant advantage of rebreathers for future biological research might prove to be the extended duration at shallow to moderate depths.

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QUESTIONS AND DISCUSSION

PHIL LOBEL: You spoke about all the advantages. One thing I wonder about, I find that diving on the rebreather keeps me warmer. I notice when you are diving in South Africa, which I always found to be incredibly cold, you are there in shorts and a shirt while everybody else is in a wetsuit, and at the end of the dive you are usually freezing. What about the warmth?

RICHARD PYLE: I would say there are two components that are valuable. One, it definitely is warmer. It was easier for me to acquire the reputation I have as a shirt-sleeve diver as opposed to a wetsuit diver because of rebreathers. If you look at old pictures of me like I showed in the open-circuit trimix, I used to wear a wetsuit. It is absolutely true that it is warmer on a rebreather. In some cases where we have 85°F (29°C) shallow decompression, that actually works against us. It gets to the point where you do not want to exert because the heat from the absorbent. What I actually find even better than the warmth is the humidity. On open-circuit you get that sort of dry, scratchy throat thing from the cold dry air. On the rebreather dives I have never really gotten that. I did not put those up there because they were not specific to biological diving. They are more generic advantages to rebreathers. But I agree with you about the warmth factor benefit.

PHIL LOBEL: It is good for the science because if you are warm and good, you are focused.

MARK KEUSENKOTTEN: I was just wondering if anyone has done the sort of work you have done in the twilight zone in the Atlantic.

RICHARD PYLE: I am not the best person in this room to speak about it. I think Doug and others in the room could talk about it much more about it.