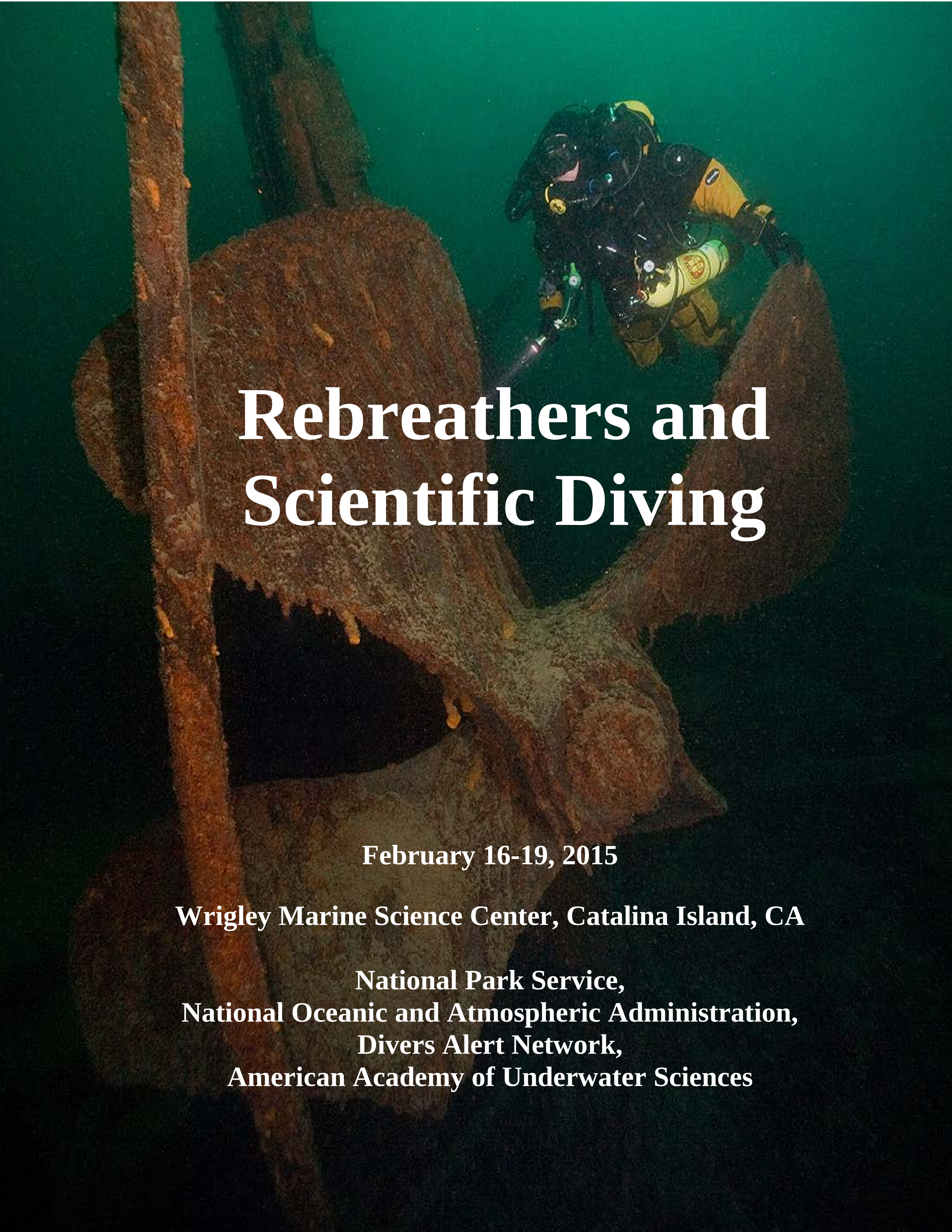


Rebreathers and Scientific Diving

February 16-19, 2015

Wrigley Marine Science Center, Catalina Island, CA

National Park Service,
National Oceanic and Atmospheric Administration,
Divers Alert Network,
American Academy of Underwater Sciences

Rebreathers and Scientific Diving

Workshop Proceedings

February 16-19, 2015

Jointly Sponsored by

National Park Service
National Oceanic and Atmospheric Administration
Divers Alert Network
American Academy of Underwater Sciences

Editors
Neal W. Pollock, PhD
Steven H. Sellers
Jeffrey M. Godfrey

citation:
Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Wrigley Marine Science Center, Catalina Island, CA; 2016; 272 pp.

This workshop and the publication of this document were jointly sponsored by National Park Service (NPS), National Oceanic and Atmospheric Administration (NOAA), Divers Alert Network (DAN), and American Academy of Underwater Sciences (AAUS).

Cover photo credit: Brett Seymour, National Park Service. Henry Chisolm Engine, Isle Royal National Park.

ISBN # 978-0-9800423-9-9

ACKNOWLEDGMENTS

Thanks are due to NPS, NOAA, DAN, and AAUS for co-sponsoring the workshop, to participants and speakers; and those who contributed comments and suggestions for the final wording of the consensus recommendations.

We also thank Heather Fletcher, AAUS Office Manager, for logistics support; Eric Castillo, Karl Huggins and the Wrigley Marine Science Center staff for site support; Kim Farkas for recording and transcription services; and Payal Razdan for proof-reading.

Neal W. Pollock, PhD
Divers Alert Network and
Center for Hyperbaric Medicine and Environmental Physiology
Duke University Medical Center, Durham, NC

Steven H. Sellers
National Parks Service
Lakewood, CO

Jeffrey M. Godfrey
University of Connecticut

CONTENTS

Appendices

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

REBREATHERS AND SCIENTIFIC DIVING - BEST PRACTICE RECOMMENDATIONS

February 16-19, 2015
Wrigley Marine Sciences Center, Catalina Island, CA

Sponsors - NPS, NOAA, DAN, AAUS

Preamble

P1 - The Rebreathers and Scientific Diving workshop was developed as a vehicle to review standards, practice, physiology, incidents and equipment evolution relevant to scientific diving with rebreathers. The primary goals were to enhance cross-agency communication and to produce a best practices template available to the community. The program involved 18 hours of structured sessions over three days - lecture, discussion, and practical - with unstructured time for additional interactions.

P2 - These recommendations are offered for consideration of the scientific diving and related communities, and may not be applicable in all situations. We recognize that the ultimate authority for the authorization of users and approved equipment and operations lies with the institution. The items discussed reflect the issues of special concern identified by participants, but the list is not exhaustive. The product should be considered as an iterative, not final, effort. Technological evolution and practice development will introduce new elements that should be considered. A periodic review of issues, both ongoing and emerging, will be required.

Research Priorities

R1 - Collect, review and publish data evaluating the efficacy and validity of oxygen exposure limits (including CNS, pulmonary, hyperoxic myopia, and setpoint selection)

R2 - Evaluate the efficacy of breathing-loop disinfection products and protocols

R3 - Collect, review and publish data evaluating oxygen handling in field operations

R4 - Collect, review and publish data evaluating the use of full-face masks and mouthpiece retaining devices

R5 - Continue efforts to develop and implement reliable CO_2 monitoring technologies

R6 - Evaluate the efficacy and utility of oxygen cell testers and oxygen cell validation protocols

R7 - Collect, review and publish data evaluating the efficacy of different practices to store packed and partially used CO_2 absorbent material.

Workshop Priorities

W1 - A number of critical issues identified in this meeting are complex enough to require more extensive deliberation. It is recommended that dedicated workshops are conducted to collect, review and publish information evaluating practice and safety on the following topics as they relate to scientific diving:

W2 - Mixed team operations - cross-training, gas sharing, surface support, emergency procedures

W3 - Bailout Strategies - supply requirements, equipment configurations (e.g., bailout valves, staged bailout, shared bailout). Bailout strategies are complex and are specific to individual circumstances and available equipment.

W4 - Diver training - prerequisites, initial training requirements, skill elements, depth progression, proficiency assessment, progressive workup requirements (general qualification and project-specific), task-load management, skill maintenance, cross-over training requirements, training requirements for non-divers (straight to rebreather), and retraining after break from diving.

Recommendations to Manufacturers

M1 - Alarms for life-critical failure states should be designed to be:
1. Unambiguously differentiated from standard instrumentation monitoring displays to reduce the possibility of being overlooked or ignored by the diver;
2. Expressed to the diver via at least two different sensory modalities (visual, auditory, or tactile);
3. Detectable by other members of the dive team without action on the part of the diver.

Note: Consideration of human factors engineering of alarm systems from complementary disciplines such as automotive, aviation and aerospace safety engineering may prove fruitful for future improvement and/or standardization of critical alarm systems.

Operational Recommendations

O1 - Abnormal (off-nominal) events or incidents involving rebreather function, even minor, should be documented. Where appropriate, the information should be shared with the broader community.

O2 - Institutions should capture, maintain, and share detailed information in standardized format about individual dives and divers (appropriately de-identified). This includes dive computer downloads (e.g., comprehensive time-depth profile, gas mix[es], PO_2), diver demographics, and diver condition (e.g., perceived workload, thermal stress, health outcome).

O3 - A system for aggregating data on diving activity within the scientific community, including data exchange standards and protocols and data management tools should be developed.

O4 - AAUS rebreather standards should be updated and standard operating procedures documented.

O5 - Rebreather modifications (including consumables and operational limits) that deviate from or are not covered by manufacturer documentation should be discussed with the manufacturer and approved by the DCB prior to implementation.

O6 - Calculation of respired gas density should be part of dive planning. Ideally, densities should be less than 5 $g \cdot L^{-1}$, and should not exceed 6 $g \cdot L^{-1}$ under normal circumstances.

O7 - Elevated physical exertion can produce numerous risks to diver safety, including CO_2 retention, increased decompression stress, and increased susceptibility to oxygen toxicity. Management of diver exertion should be considered as part of dive planning. Optimally, physical exertion during periods of gas uptake should be kept as low as practicable. Light exercise during shallow phases of the dive may help to safely increase inert gas elimination, but higher intensities may promote bubble formation.

O8 - A switch from helium to nitrogen-based diluent during decompression is associated with a small increase in the risk of inner ear DCS. While this does not preclude diluent switches, in the majority of circumstances decompression safety may be best served by remaining on a single diluent. Bailout from helium-based gas to gases with higher nitrogen content can be justified by circumstance and are not covered by this statement.

O9 - Unit-specific checklists should be used to ensure completion of essential steps in both the pre-dive and the final pre-water entry phases.

O10 - The diver should 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.

O11 - Optimal rebreather configuration would provide the diver and rescuers with the ability to change the diver's breathing supply source from the breathing loop to an alternate, known safe breathing gas supply (open-circuit or redundant rebreather system) without the removal of the rebreather mouthpiece or full-face mask unless such a configuration creates additional risk (for example, systems incorporating gas mixtures which might be unsafe to breathe at certain depths should incorporate additional measures to prevent such an occurrence). Optimally, such configurations should be designed to be reliably activated with minimal delay and in a one-handed manner.

O12 - Divers are responsible to ensure that they are in good health and maintain fitness for diving. The decision to dive is that of the diver. A diver may refuse to dive, without fear of penalty or reprisal, whenever he or she feels it is unsafe to do so. The ultimate responsibility for safety rests with the individual diver. It is the diver's responsibility and duty to refuse to dive, if, in his or her judgment, conditions are unsafe or unfavorable, or if they will be violating regulations or the precepts of his or her training.

O13 - The prebreathe duration should be sufficient to verify control and monitoring system functions. The prebreathe procedure cannot reliably detect a missing or compromised scrubber. The prebreathe should be conducted as close to the start of every dive as practicable.

O14 - Where applicable during initial build, manual negative and positive tests should each be maintained for a minimum of one minute.

O15 - Management of an unresponsive rebreather diver should be included in diver training. Accident response plans and forms should be developed (refer to UHMS guidelines; Mitchell et al. 2012).

O16 - When conducting mixed team training team members should be able to recognize life-threatening events and provide emergency support. All team members should have access to alternate emergency breathing gas.

O17 - When conducting cross-platform rebreather and mixed- or cross-mode diving team members should have operational familiarity with each other's equipment and be able to effect both assist and rescue procedures.

O18 - The minimum annual rebreather diving activity to maintain currency should be 12 dives with a minimum 12 h underwater time. It must be noted, however, that the minimum level is insufficient for some rebreather diving activities. Diving Control Boards should review and establish rebreather minimum use and diver proficiency standards that are appropriate to maintain currency for their organizational activities. To count toward currency, dives should be at least 30 min in duration.

O19 - Pre-operation workup dives are recommended to verify diver competency. They need to include review and practice of emergency recognition and response skills and management of task loading. A schedule of progressive workup dives is most important after significant periods of inactivity.

Deferred Topics List

Editors' note: A number of topics or issues were raised during the workshop that could not be adequately addressed in the time available or with the resources in hand. The list expanded and contracted as we progressed, leaving the following items for future consideration.

Environment progression schedule
Topside support recommendations/considerations
Guardian Angel (partner diver tasked solely with monitoring a working diver) requirements
Multi-institutional operations
Days off, operational limits, fatigue
Rebreathers approved for program use
Third party testing requirements / Vetting of third party equipment reviewers
Approval of decompression algorithms
Real-time diver tracking and monitoring
Information on rebreather support and requirements for non-rebreather supervisors

Reference

Mitchell SJ; Undersea and Hyperbaric Medical Society Diving Committee. Guidelines for rescue of an unresponsive diver from depth. Diving Hyperb Med. 2013; 43(3): 168-70.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

An Overview of Rebreathers in Scientific Diving 1998 – 2013

Steven H. Sellers

National Park Service, 12795 W. Alameda Parkway, Lakewood, CO 80228, USA
Steven_Sellers@nps.gov

Abstract

A review of rebreather use in the scientific diving community from 1998 – 2013 based on 10,200 individual dive logs made by 221 divers from 20 different organizations as well as summary statistics and incident reports submitted to the American Academy of Underwater Sciences (AAUS) statistical database. The study provides a summary comparison of scientific open-circuit and rebreather diving during the sample period, an overview of the population of scientific rebreather divers, the rebreather platforms used, the general purpose of the rebreather dives conducted (training or scientific), specialized environments in which rebreathers are being used for scientific diving, breathing gases being employed, and depth ranges where scientific divers are training and working. The data indicates a trend toward increasing numbers of rebreather dives and rebreather divers within the scientific diving community.

Keywords: safety, closed-circuit, hypoxia, semiclosed-circuit, accident, incident, safety AAUS

Introduction

Rebreathers in scientific diving have a long, complicated history. That is not the subject of this presentation. This is a snapshot of rebreather use in the scientific diving community in the recent past. It is not the complete picture, and it does not claim to be without flaws.

The summary statistics available through the American Academy of Underwater Sciences (AAUS) database are generally used to provide a cursory view of the AAUS diving activity. They have clear limits in providing a more in depth look at rebreather use in the scientific diving community. This presentation will review the content and limitations of the AAUS database, and supplement the AAUS data with information submitted from individual diver logs.

The AAUS Statistical Record

The AAUS statistical records predate the creation of their online data collection system. However, collection criteria prior to 1998 were not as well-defined, and tended to lack a degree of consistency from year to year. Since 1998 the data collection criteria have been consistent and uniform, and provide a good basis for comparison. Therefore, the early limit for this study was set at 1998, the first year of the online AAUS dive statistical database. Data were reviewed through 2013.

There are three major limitations of the AAUS statistics database. The first is the summary nature of the data collected. The Academy does not collect the individual dive log entries from its entire membership; that information resides with the individual Organizational Member (OM). The second limitation is a function of AAUS membership. Scientific diving conducted by unaffiliated organizations and individuals is not collected or represented. The third limitation is that close calls and even incidents that were successfully managed before significant insult developed may not be reported.

A review of the AAUS database identified 52 OMs reporting rebreather dives between 1998 and 2013. During this time their divers logged 10,988 rebreather dives for a total of 594,932 min (approximately 9,915.5 h). Three incidents were reported in association with these exposures, one case each of decompression illness, idiopathic immersion pulmonary edema, and hypoxia (Table 1). Incident descriptions are presented as submitted to AAUS had have not been modified by the author.

The AAUS summary statistics included in this report were supplemented by the data provided by four non-AAUS organizations. Each is or was a US Federal unit with a very active diving program that included substantial rebreather operations. This increased the summary data for rebreather dives logged between 1998 and 2013 by 43% to 15,767 dives logged by a total of 56 discrete organizations. This constituted 833,971 min of dive time (approximately 13,899.5 h). The additional data also included three additional reported incidents, one case of oxygen toxicity, one nonfatal drowning associated with an oxygen convulsion, and one case involving asymptomatic decompression concern that involved treatment with a USN Table 6 out of caution due to the circumstances of the dive (Table 2).

Table 1. Incident descriptions from AAUS Database

Year:	2011
AAUS Incident ID:	130
Diving Purpose:	Scientific
Diving Gas:	Air
Diving Mode:	Rebreather
Decompression Planning and Calculation Method:	Dive Computer
Specialized Environment:	Required Decompression
AAUS Depth Range:	151-190 ft (46-58 m)
Incident Type:	Hyperbaric
Incident Rating Scale:	Moderate
Did this incident involve a workman's compensation claim?	No
Describe the circumstances surrounding this incident and the extent of the injuries or illness:	Research dive to 148 ft (45 m), bottom time 27 min, total time 108 min, on Megalodon rebreathers with air diluent. No deviation from decompression schedule, according to online Shearwater Predator and VR3 computers. Two divers qualified on the Meg. Three hours after exiting the water, one of the divers complained about dizziness, disorientation, weakness and showed spots on her skin.
Describe the treatment provided and results:	She was put on O_2 and was evacuated by EMS to the local hospital and hyperbaric facility. After initial examination she was treated in the chamber for more than seven hours with CX30 treatment tables (50% O_2/50% He 30 m) and was asymptomatic at the end. A follow-up examination found no residual effects.
Recommendation to avoid repetition of incident:	More conservatism; proper hydration and rest before deep dives.
Other details:	On medical recommendation she avoided diving for eight weeks.

Year:	2012
AAUS Incident ID:	139
Diving Purpose:	Scientific
Diving Gas:	Nitrox
Diving Mode:	Rebreather
Decompression Planning and Calculation Method:	Dive Computer
Specialized Environment:	N/A
AAUS Depth Range:	0-30 ft (0-9 m)
Incident Type:	Hypoxia/Hypercapnea
Incident Rating Scale:	Moderate
Did this incident involve a workman's compensation claim?	No
Describe the circumstances surrounding this incident and the extent of the injuries or illness:	On this date one of our qualified Megalodon divers was planning to dive to 148 ft (45 m) with air diluent, to a deployed experiment. The diver was accompanied by an open-circuit technical diver. Both planned to use scooters for propulsion. The Megalodon diver claimed that they made a complete pre-dive check according to the checklist, including a breathing check. A few minutes after entering the water (still at standing depth) the victim's partner started yelling that something is wrong with victim and proceeded to pull them up to the surface. The victim reacted that there was nothing wrong and convinced everybody that they were OK to dive. The two divers decided to close the distance to the experiment site in shallow water (6-10 ft [2-3 m].) using the scooters. A couple of minutes after they were on their way the partner noticed that the Meg diver was on his back and partner immediately pulled the victim up to the surface and started yelling for help. Partner said later that victim still had the DSV in his mouth and the partner removed it on the surface. I arrived at the scene two or three minutes later and saw that victim was conscious but very confused. Checking the primary display the PO_2 (on the surface) was 0.15 ATA And the solenoid O_2 hose with the Swedgelock QC4 was disconnected.
Describe the treatment provided and results:	Victim was treated with O_2 and was sent to the hospital for follow-up where they kept victim on O_2 for a few hours since his O_2 blood saturation was low.
Recommendation to avoid repetition of incident:	Closer involvement of the DSO in all aspects of planning, preparations and conducting all technical dives
Other details:	No other details

Year:	2012
AAUS Incident ID:	141
Diving Purpose:	Scientific
Diving Gas:	Air
Diving Mode:	Rebreather
Decompression Planning and Calculation Method:	Dive Computer

Specialized Environment:	Required Decompression
AAUS Depth Range:	101 to 130 ft (30-40 m)
Incident Type:	Other
Incident Rating Scale:	Serious
Did this incident involve a workman's compensation claim?	No
Describe the circumstances surrounding this incident and the extent of the injuries or illness:	Scientific diver, 300 ft (90 m) depth rating, endorsements for dive computer, CCR, nitrox, mixed gas, stage decompression. After entering the program as an experienced diver from another AAUS institution and completing the SDQC, the diver has logged 123 dives, including 65 CCR dives comprising 95.5 h dive time; 20 dives have been logged to depths in excess of 130 fsw (40 msw). Supporting staff on site included DSO/buddy; support diver, vessel operator, topside support. Activity: Dive objectives were twofold. The primary objective was recovery of Artificial Reef Modules (ARM) with photo/video documentation of ARMs in situ and of the recovery process. The dive was also intended as a work-up for Diver's return to diving, in preparation for deeper planned activity in support of the same project. ARM recovery entails only moderate exertion on the bottom. The dive team was to recover a total of six ARMs, each constructed of stacked 3/8" PVC panels forming a porous cube with dimensions of approximately 16" x 16" x 16". With an in-water weight of approximately 4 lb (2 kg), an ARM is easily handled by a diver on the bottom. For recovery, each ARM is covered with a plastic cap (milk crate lined with nitex screen) cinched into place with two webbing straps before being sent to the surface with a lift bag attached by carabineer. Approximately 5 lb (2.3 kg) of lifting force was required to start the ascent of each ARM. Both divers were equipped with Inspiration Vision closed-circuit rebreathers (CCR) using air diluent. Divers operated at a constant PO_2 setpoint of 1.3 ATA at working depth, and 0.7 ATA setpoint shallower than 20 fsw (6 msw) during ascent. Each diver carried a 30 ft^3 cylinder of 32% oxygen nitrox for open-circuit bailout, and a second 50 ft^3 cylinder of 50% oxygen nitrox. The latter cylinder was primarily intended to inflate lift bags to recover the ARMs, but was also available for the divers if needed at depths shallower than 70 fsw (21 msw) (MOD of EAN50 @ PO_2 limit of 1.6 ATA). Additional decompression gas was staged in the support vessel with protocols for its deployment in the event it was needed. The divers completed ascent using only the CCR. Divers conducted all pre-dive equipment preparation and leak checks successfully, including in-water assessment for CCR bubble leaks immediately after immersion. The dive proceeded normally and uneventfully through descent and bottom working phases. At approximately 35 min elapsed dive time and after working phase was complete, Diver deployed a surface marker buoy from their line reel as an ascent line and divers initiated ascent per normal procedures. Support diver entered the water,

	sent down an 80 ft^3 cylinder of 50% oxygen nitrox bail-out gas, and followed down to the dive team, according to normal procedure.
Describe the treatment provided and results:	Incident and Resolution: After the working phase was complete and shortly before the start of ascent, Diver indicated to buddy feeling chest tightness and started coughing. Diver's severe coughing continued throughout the dive team's controlled ascent and decompression of ~17 min, and during the post-dive transit to boat ramp (~30 min). Upon arriving at harbor and with symptoms continuing, the victim was placed on oxygen and Diving Medical Officer and HTC Medical Director were called for phone consultation. Per advice, EMS was called and the diver transported to ER. Albuterol nebulizer treatment was negative for symptom relief. Chest X-ray was diagnostic for pulmonary edema. Administration of Lasix (diuretic) resulted in symptoms lessening to resolution. Diver was released from the ER after two hours of observation.
Recommendation to avoid repetition of incident:	Findings and Recommendations: No evidence of equipment malfunction or procedural error is evident. Medical diagnosis by attending physician was idiopathic immersion pulmonary edema. Lack of resolution with Albuterol administration indicates event was probably not related to asthma or allergens. MD Recommendations: Follow up with personal physician. Required exams and testing prior to clearance for further diving to be determined, and are pending discussion by Diver, DSO, DMO. Diver will refrain from diving until satisfactory explanations and evaluations are forthcoming.
Other details:	Equipment: While diver and DSO were at the hospital, the diver's rebreather was returned to the Dive Locker, externally rinsed and the oxygen and diluent supply cylinders removed by Logistics Specialist. After return from the hospital, Diver and DSO disassembled and cleaned the rebreather and downloaded its electronic dive log. Normal to slightly elevated amounts of exudate fluid were noted in the exhalation counterlung. The CO_2 absorbent canister, CO_2 absorbent, electronics head, inhalation counterlung and inhalation-side hoses contained only normal to less than normal amounts of condensate moisture. This is consistent with the diver's production of fluids during coughing, with no other leaks. Diver reported no unusual taste or odor in the breathing supply at any phase of the dive. Diver's gas supply cylinders were filled from the UHDSP dive locker fill station and contained expected post-dive pressures. Gas analysis indicates proper oxygen content in both cylinders, also with no unusual odor or taste noted by the DSO or Logistics Specialist. The battery compartments in the Diver's unit were upgraded by the manufacturer in the Fall of 2011 to new redesigned type, sealed against pressure differentials of up to 20 ATA. Battery compartments were opened and no evidence of internal pressurization was observed. No evidence of water ingress into or leakage from the battery compartments was seen. Data was downloaded from the Diver's and partner's electronics. Time and

	date log on Diver's CCR electronics were incorrect. Downloaded data indicate that PO_2 was controlled properly, with sensor readings within manufacturer's tolerances. No warnings for hypoxia, hyperoxia, or oxygen sensor drift occurred. Estimated oxygen exposures experienced by Diver were 27% peak CNS, 24% peak OTU, and are well within planned levels and accepted safe limits. Decompression controls were set to incur no greater than 85% of allowable supersaturation, and no violation of decompression or ascent rate requirements were recorded. The CO_2 absorbent temperature monitor indicated proper thermal behavior of the absorbent bed during the dive. The Diver's symptoms were not consistent with CO_2 excess.

Table 2. Incident reports from non-AAUS contributors.

Year:	2012
Incident ID:	Not Provided
Diving Purpose:	Scientific
Diving Gas:	Nitrox
Diving Mode:	Rebreather
Decompression Planning and Calculation Method:	Dive Computer
Specialized Environment:	Required Decompression
AAUS Depth Range:	101 to 130 ft (30-40 m)
Incident Type:	Other
Incident Rating Scale:	Serious
Did this incident involve a workman's compensation claim?	Yes
Describe the circumstances surrounding this incident and the extent of the injuries or illness:	Oxygen Toxicity
Describe the treatment provided and results:	Details not Provided
Recommendation to avoid repetition of incident:	Details not Provided
Other details:	Details not Provided

Year:	2012
Incident ID:	Boulder Basin – Diver 1
Diving Purpose:	Training
Diving Gas:	Nitrox
Diving Mode:	Rebreather
Decompression Planning and Calculation Method:	Dive Computer
Specialized Environment:	Required Decompression
AAUS Depth Range:	101 to 130 ft (30-40 m)
Incident Type:	Near Drowning / Hypoxia
Incident Rating Scale:	Serious
Did this incident involve a workman's compensation claim?	Yes
Describe the circumstances surrounding this incident and the extent of the injuries or illness:	Diver experienced an oxygen convulsion at depth and aspirated water. Diver was discovered in convulsion at depth by dive buddy. The diver's rebreather loop was out of the diver's mouth and closed. The diver's off board bailout regulator had been

	deployed and was free flowing into the water column. The dive buddy attempted to place the diver's bailout regulator in the injured diver's mouth but could not due to clenched jaws. The buddy inflated the diver's BCD and began swimming the injured diver to toward the surface. At approximately 70 ffw (21 mfw) the dive buddy released the injured diver into the water column and attempted to regain control of her ascent rate. The injured diver's ascent rate continued to increase. Last recorded ascent rate in 20 ft (6 m) of water was 197 ft (60 m) per minute. The injured diver was recovered at the surface by onsite support personnel, found to be not breathing with a frothy sputum around the mouth and nose. The diver's pupils were reactive to light.
Describe the treatment provided and results:	Rescue breaths, Oxygen, Airway, Air evacuation, US Navy Treatment Table 6; diver kept unconscious in ICU for 2.5 days. Diver had zero deficits upon waking. Diver has returned to full duty including rebreather diving.
Recommendation to avoid repetition of incident:	Equipment review found the rebreather to be assembled correctly. The unit had returned from factory service approximately three months prior to the incident. Inspection of the oxygen cells found them to be 33 months old, well beyond the 18-month maximum use range from date of manufacture. Discussions with the manufacturer found their service practices had changed and oxygen cells were not automatically being replaced at service as expected. The incident review also found the diver had not verified the age of their unit's oxygen cells. Standards and policies were changed at both the manufacture and institution level to require more regular checking of the dates on oxygen cells.
Other details:	The diver received an alert from the rebreather electronics of a cell being out of range. The alert was received at a point during the dive where it was expected, on descent near automatic setpoint switch. The alert was displayed as a blue/green flashing light on the diver's HUD and the words "cell millivolt error" on the diver's primary handset. The diver reported seeing the error, but not remembering its significance. The diver checked the PO_2 readings and did not see enough deviation to raise an alarm. After two minutes of flashing, the unit discontinued the blue/green alert as programed to save battery. No other alerts or alarms were recorded by the unit pre-incident. The investigation found that two of the three oxygen cells had become current limited and could not detect the high end of the oxygen scale. This limited state was just below the setpoint, causing the unit to inject higher than needed levels of oxygen into the diver's breathing loop throughout the dive leading to the oxygen convulsion at depth.

Year:	2012
Incident ID:	Boulder Basin – Diver 2
Diving Purpose:	Training
Diving Gas:	Nitrox
Diving Mode:	Rebreather

Decompression Planning and Calculation Method:	Dive Computer
Specialized Environment:	Required Decompression
AAUS Depth Range:	101 to 130 ft (30-40 m)
Incident Type:	Hyperbaric
Incident Rating Scale:	Minor
Did this incident involve a workman's compensation claim?	Yes
Describe the circumstances surrounding this incident and the extent of the injuries or illness:	Diver experienced a fast ascent from 120 to 70 ft (37 to 21 m) while performing a rescue of a convulsing dive buddy. Diver released dive buddy back into the water column, gained control of her ascent rate, drifted back to the bottom where she shot a lift bag and ascended. Upon surfacing, the diver's offboard dive computer showed one minute of missed decompression, onboard computer was clear.
Describe the treatment provided and results:	Diver was placed on O_2, transported to hospital to be checked out and received a USN Table 6 (precautionary). Diver was treated and released with no deficits.
Recommendation to avoid repetition of incident:	No recommendations at this time
Other details:	N/A

Table 3. Rebreather use captured in the AAUS database, supplemented with data from four non-AAUS organizations

Organization	**Time (min)**	**Number of Dives**
Aquarium of the Pacific	4392	69
Bermuda Institute of Ocean Sciences	174	4
Boston University	1248	33
California Academy of Sciences	9714	133
California State University	10	1
California Department of Fish & Wildlife	26592	1370
California Science Center Foundation	285	4
California State University Monterey Bay	1029	26
East Carolina University	18217	349
Florida Fish and Wildlife Research Institute	861	10
Florida State University	1408	53
Hawaii Division of Aquatic Resources	27596	281
International Innerspace Institute Inc.	3086	53
J. F. White Contracting Co.	764	12
Marine Biological Laboratory	331	5
Monterey Bay Aquarium	1851	41
Moss Landing Marine Laboratories	97	3
National Oceanic and Atmospheric Administration (NOAA)[1]	53192	628

Organization	Time (min)	Number of Dives
National Park Service (NPS)[1]	81039	1261
NIWA New Zealand	6455	226
North Carolina Aquarium at Roanoke Island	2564	47
National Undersea Research Center (NURC)[1]	40140	497
Occidental College, Vantuna Research Group	38	1
Oregon Coast Aquarium	57	1
Perry Institute for Marine Sci., Caribbean Marine Research Center	2258	41
Prince William Sound Science Center (PWSSC)	5	1
Scripps Institution of Oceanography	13008	264
Shannon Point Marine Center	211	7
Shark Reef at Mandalay Bay	105	2
Teen Research Underwater Explorers	1546	37
Texas A&M University at Galveston	19154	268
Texas Parks and Wildlife Department	160	3
The Florida Aquarium	15700	274
The Interuniversity Institute for Marine Sciences in Eilat	22925	596
The Nature Conservancy, Hawaii Field Office	5541	76
The University of New Hampshire	19518	275
The University System of Georgia	530	8
University of Alaska	579	18
University of California, Davis	8319	118
University of California, Santa Cruz	23030	769
University of Connecticut, Marine Sciences and Technology Center	34017	605
University of Florida	27925	669
University of Hawaii	150914	1902
University of Miami/RSMAS	7374	134
University of Mississippi	7753	113
University of North Carolina at Wilmington	50013	680
University of Puerto Rico at Mayaguez, Dept. of Marine Sciences	5103	60
University of Rhode Island	822	17
University of South Florida	15900	326
University of Southern California	6948	122
University of Tasmania	19376	372
University of the Virgin Islands	12341	307
University of Washington	824	13
US Geological Survey (USGS)	64668	2393
Virginia Institute of Marine Science	55	1
Woods Hole Oceanographic Institution	16209	188
TOTAL	**833971**	**15767**

[1] Non-AAUS organizations providing data for this report.

Study Group and Review Criteria

For this review rebreather dive logs linked to individual divers were requested from OMs of AAUS, and non-member organizations known to use rebreathers as a diving mode for conducting scientific diving activities. Logs were requested from:

- Aquarium of the Pacific – AAUS OM
- Aquarius Reef Base
- Bermuda Institute of Ocean Sciences – AAUS OM
- Bishop Museum/Association for Marine Exploration
- Boston University – AAUS OM
- California Academy of Sciences – AAUS OM
- California Department of Fish and Wildlife – AAUS OM
- East Carolina University – AAUS OM
- Environmental Protection Agency (EPA)
- Florida State University – AAUS OM
- Hawaii Division of Aquatic Resources – AAUS OM
- Monterey Bay Aquarium – AAUS OM
- National Park Service – AAUS OM
- National Oceanic and Atmospheric Administration (NOAA)
- NURC (National Undersea Research Center)
- NIWA New Zealand – AAUS OM
- North Carolina Aquarium at Roanoke Island – AAUS OM
- Scripps Institute of Oceanography – AAUS OM
- Teen Research Underwater Explorers – AAUS OM
- Texas A&M Galveston – AAUS OM
- The Florida Aquarium – AAUS OM
- The Interuniversity Institute for Marine Sciences in Eilat – AAUS OM
- The Nature Conservancy, Hawaii Field Office – AAUS OM
- The University of New Hampshire – AAUS OM
- University of Alaska – AAUS OM
- University of California, Davis – AAUS OM
- University of California, Santa Cruz – AAUS OM
- University of Connecticut – AAUS OM
- University of Florida – AAUS OM
- University of Hawaii – AAUS OM
- University of Miami/RASMAS – AAUS OM
- University of Mississippi – AAUS OM
- University of North Carolina at Wilmington – AAUS OM
- University of Puerto Rico at Mayaguez – AAUS OM
- University of Rhode Island – AAUS OM
- University of South Florida – AAUS OM
- University of Southern California – AAUS OM
- University of Tasmania – AAUS OM
- University of the Virgin Islands – AAUS OM
- US Geological Survey (USGS)
- Woods Hole Oceanographic Institution – AAUS OM

For each log submitted, organizations were asked to provide:

- The date the dive was conducted, or the year the dive was conducted
- A diver identifier (name, number, initials, etc.)
- The sex of the diver
- Maximum depth of the dive, identified as feet or meters
- Dive time (surface to surface time in min)
- The purpose of the dive (Training or Scientific)
- The primary breathing gas used in the rebreather (100% oxygen, nitrox, or mixed gas [containing helium])
- A true or false indication of if the diver used a full face mask or mouthpiece retention device for the dive
- A true of false indication of if the dive required decompression stops
- A true or false indication of if the dive was conducted in an overhead environment (cavern or cave)
- A true or false indication of if the dive was conducted at altitude. For the purpose of this study altitude was defined by the US Navy Dive Manual Revision 6 (2008) section 9-13.2 "Need for Correction. No correction is required for dives conducted at altitudes between sea level and 300 ft [90 m]." "At altitudes between 300 and 1000 ft [90 and 300 m], correction is required for dives deeper than 145 fsw [44 m] (actual depth). At altitudes above 1000 ft (305 m), correction is required for all dives."
- The rebreather make/model used for the dive
- A true or false indication of if the diver experienced a reportable dive incident on this dive. (required hyperbaric treatment, serious physical injury requiring hospitalization, death)

Twenty organizations provided individual dive logs. One organization (USGS) provided additional summary data not available in the AAUS database. Responding organizations provided logs in either electronic or paper format. Electronic formats ranged from Excel spreadsheets to, in one case, submission of a copy of the organization's entire Access database of dives. Paper formats included copies of actual field logs, printouts from field reports, or copies of divers hand written dive logs. The organizations submitting rebreather dive logs for this review were:

- Bishop Museum/Association for Marine Exploration
- California Academy of Sciences – AAUS OM
- California Department of Fish and Wildlife – AAUS OM
- East Carolina University – AAUS OM
- Hawaii Division of Aquatic Resources – AAUS OM
- National Park Service (NPS) – The NPS is a new AAUS OM, but was not an OM during the time frame of this study. NPS dive statistics prior to 2014 are not included in the AAUS statistical database.
- National Oceanic and Atmospheric Administration (NOAA)
- National Undersea Research Center (NURC)
- Scripps Institute of Oceanography – AAUS OM
- The Florida Aquarium – AAUS OM
- The Interuniversity Institute for Marine Sciences in Eilat – AAUS OM
- The University of New Hampshire – AAUS OM
- University of California, Davis – AAUS OM
- University of California, Santa Cruz – AAUS OM
- University of Connecticut – AAUS OM
- University of Hawaii – AAUS OM
- University of Mississippi – AAUS OM

- University of North Carolina at Wilmington – AAUS OM
- University of Rhode Island – AAUS OM
- Woods Hole Oceanographic Institution – AAUS OM

Logs Submitted Outside of the Study Time Range

Several organizations submitted logs beyond the requested 1998 to 2013 date range. These logs were included in the master log file and will be referred to for additional context in some cases, but the concentrated focus of this review will stay in the 1998 to 2013 timeframe.

The earliest rebreather dives reported for this effort were 13 training dives done by five NURC divers in 1988. The dives were performed using a Biomarine CCR 1000 and amassed 364 min of dive time (Figure 1). There was then a break in the logs submitted until 1992 when the University of California Santa Cruz (UCSC) provided logs for dives conducted on a Cobra 100% oxygen rebreather. Use of the Cobra was the only rebreather platform reported for 1992 and 1993, and all dives were listed as scientific in purpose. In 1994 the USCS logs were joined by logs submitted by the Bishop Museum/Association for Marine Exploration using the Cis-Lunar MK-4P. These Cis-Lunar logs involved training and scientific dives and listed use of nitrox and mixed gas as diluent.

Dives submitted for 1995, 1996, and 1997 consisted of logs for six divers from three organizations (UCSC, Bishop Museum/Association for Marine Exploration, and the University of Hawaii [UH]). Scientific dives dominated the logged purposes, 366 Scientific to 12 training dives. Seven different rebreather platforms were listed, two different 100% oxygen units (the Cobra, and the Lar V), three semi-closed units (the Fieno, Halcyon, and the Draeger Dolphin [dives submitted on the Atlantis were included as Draeger Dolphin to simplify tabulation]), and two CCRs (the Cis-Lunar MK-4P, and the Cis-Lunar MK-5P) (Figure 2). These three years are significant in that they include the first rebreather dives logged, submitted for this review, at depths greater than 190 fsw (58 msw). Sixty-six dives were logged by the Bishop Museum/Association for Marine Exploration using the Cis-Lunar MK-4P and Cis-Lunar MK-5P for scientific purposes from depths of 192 fsw (59 msw) down to 420 fsw (128 msw). Three of the dives conducted in 1995 are the first instance in the submitted samples where a full-face mask/mouthpiece retention device was listed as used.

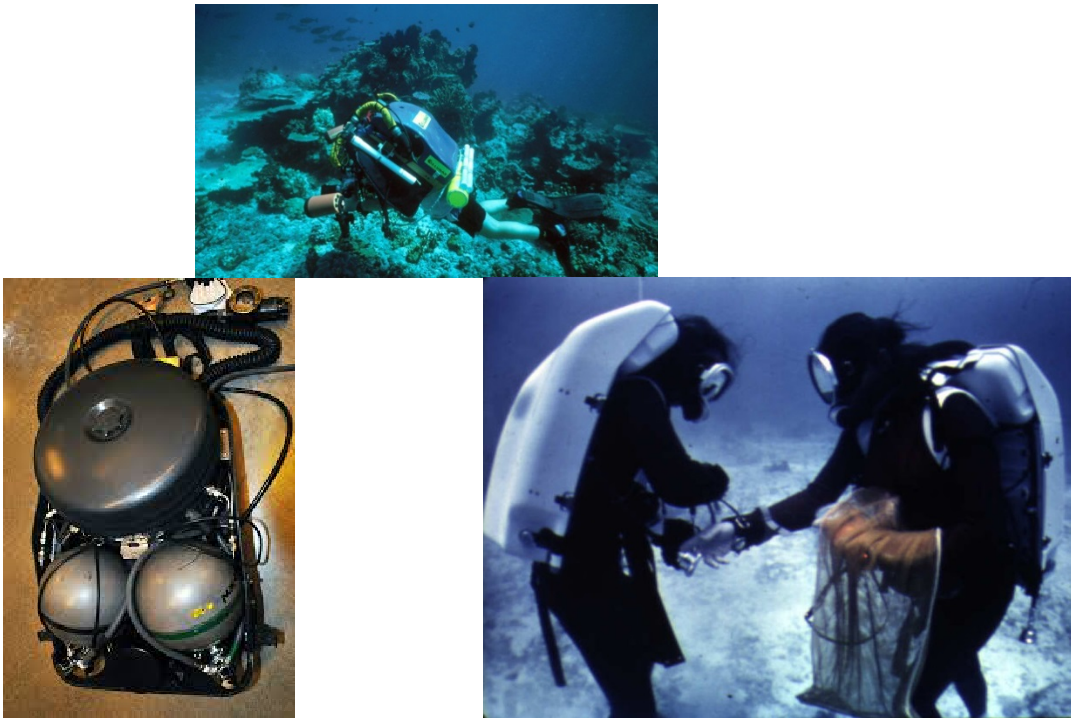


Figure 1. Upper photo: Richard Pyle using the Cis-Lunar MK-4P for decompression operations in Papua New Guinea, 1995 (photo courtesy Richard Pyle). Lower left and lower right: Biomarine CCR 1000.

Figure 2. Cis-Lunar MK-5P (photo courtesy Richard Pyle).

Open-Circuit vs Rebreather Dives

The AAUS statistical database references 1,675,350 open-circuit (OC) dives logged from 1998 through 2013, totaling 69,826,983 min of dive time (1,148,783 h) (Figure 3). During this same time period, AAUS OMs logged 10,988 rebreather dives for a total of 594,932 min of dive time (approximately 9,915.5 h). The rebreather diving captured represents <0.7% of the number and

<0.9% of the underwater time logged for OC dives. Stated another way, there were 152-times more dives and 116-times more underwater time logged for OC diving than rebreather diving in this sample.

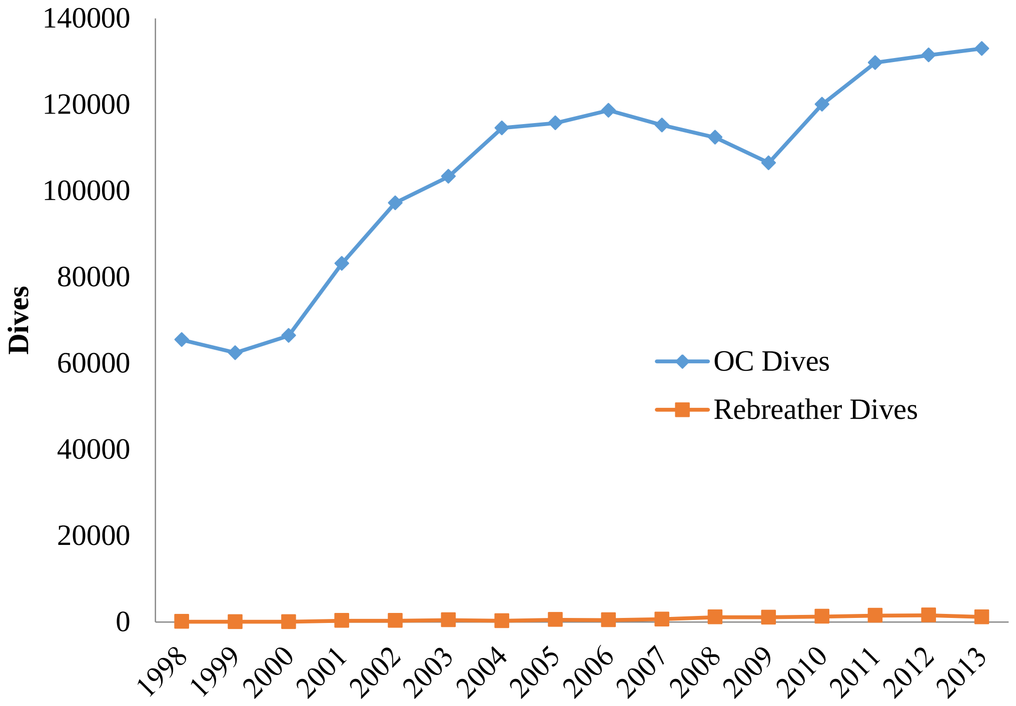


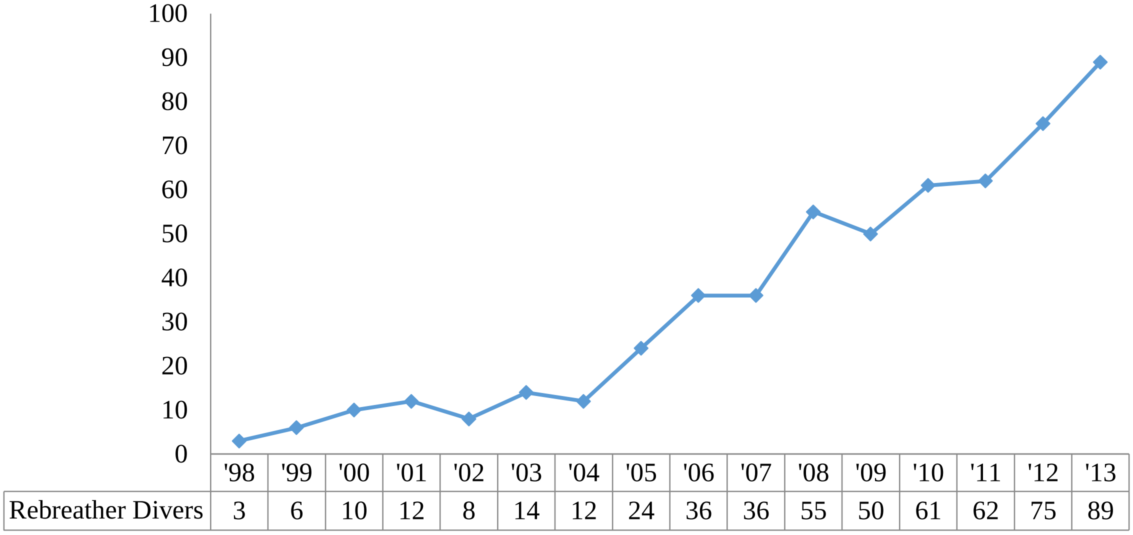
Figure 3. Open-circuit vs rebreather dives (AAUS OMs)

Comparing the number of AAUS OC divers logging dives annually with the number of AAUS rebreather divers logging dives annually produces a very similar graph. Such comparisons succeed in demonstrating that OC scuba is currently still the dominant mode used in scientific diving. They do little to shed light on rebreather use in the scientific diving community. For that we need to look at actual log data, not summary statistics.

Due to a number of factors, the criteria for dive logs used in this review were very simplistic. The information being collected by users on field logs is not universal or consistent. The criteria being collected to compile summary statistics is worse. Documented information on the PO_2 settings, decompression algorithms, or algorithm conservative settings used when conducting a dive was virtually nonexistent in submitting organizations data collection protocols. The field log structure of the data collected is also summary in nature, relying on maximum depth and time exposures to characterize a dive, rather than more in depth records available on rebreather platforms with onboard electronics and dedicated systems monitoring/recording capabilities. This represents a significant loss of important information, and is but one example of how the community could improve its record keeping and produce more usable information for future reviews.

The Population

The submitted individual dive logs identified 221 divers logging rebreather dives between 1998 and 2013 (Figure 4). Eighty-eight percent were male (n=194) and 12% female (n=30) (Figure 5). Males logged 4,468 training dives for 261,932 min of dive time, and 4,897 scientific dives for 370,801 min of dive time. Females logged 25,979 min of dive time over 379 training dives and 37,227 min of dive time over 456 scientific dives (Figure 6). Females logged more underwater time on average in training dives than males (69 min vs 59 min, respectively), with a smaller increase in the average underwater time logged on scientific dives (82 min vs 76 min, respectively). The available data do not provide an explanation for these differences.



	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13
Rebreather Divers	3	6	10	12	8	14	12	24	36	36	55	50	61	62	75	89

Figure 4. Rebreather divers by year, 1998-2013.

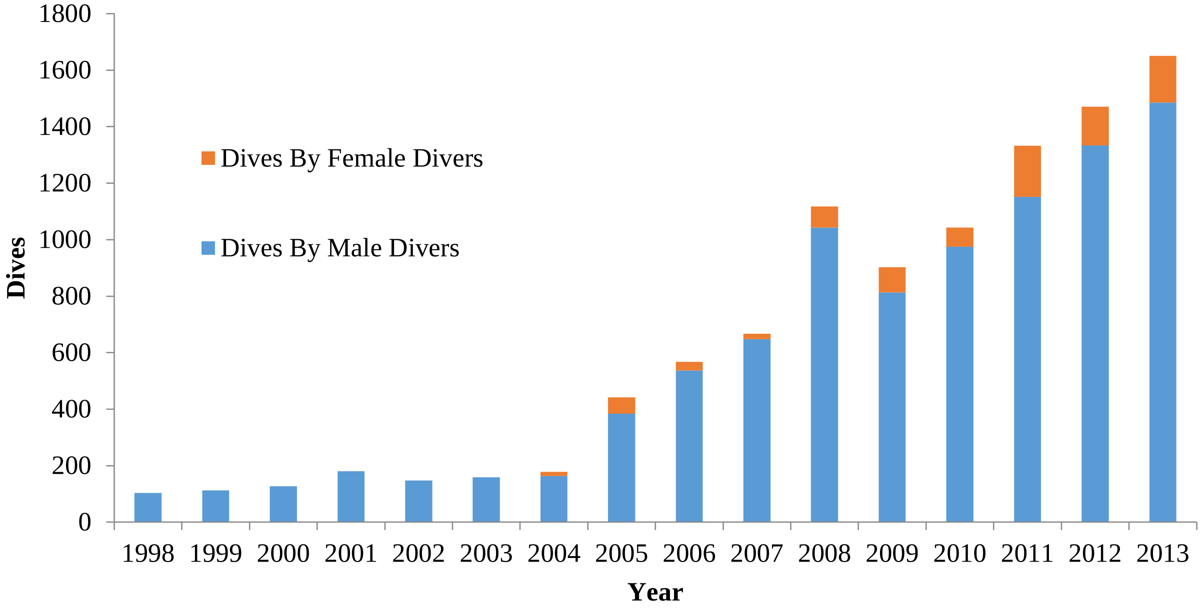


Figure 5. Rebreather dives logged by year, 1998-2013.

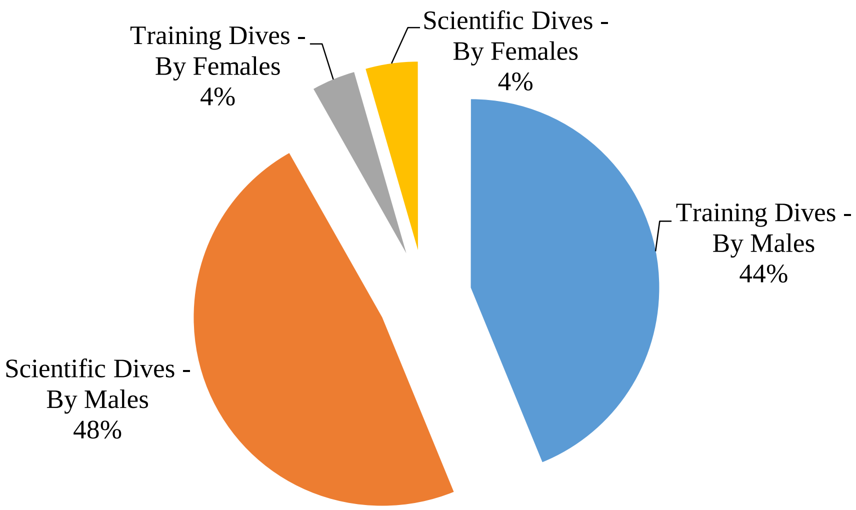


Figure 6. Rebreather divers by categorical activity and sex, 1998-2013.

Rebreather Platforms

Within the 1988 to 2013 sample period, 17 rebreather models were reported used by 20 organizations (Figure 7). These organizations reported 10,200 individual logs for 221 divers and 695,939 min of dive time. All 17 rebreather types and models are referenced in Figure 7. Oxygen rebreathers and multi gas units were then separated out to provide a more useful comparison. There were two dives reported on the Exosuit. These were excluded from the comparison of multi gas rebreathers due to the uniqueness of the Exosuit platform (a one atmosphere suit requiring larger vessel support for deployment and recovery).

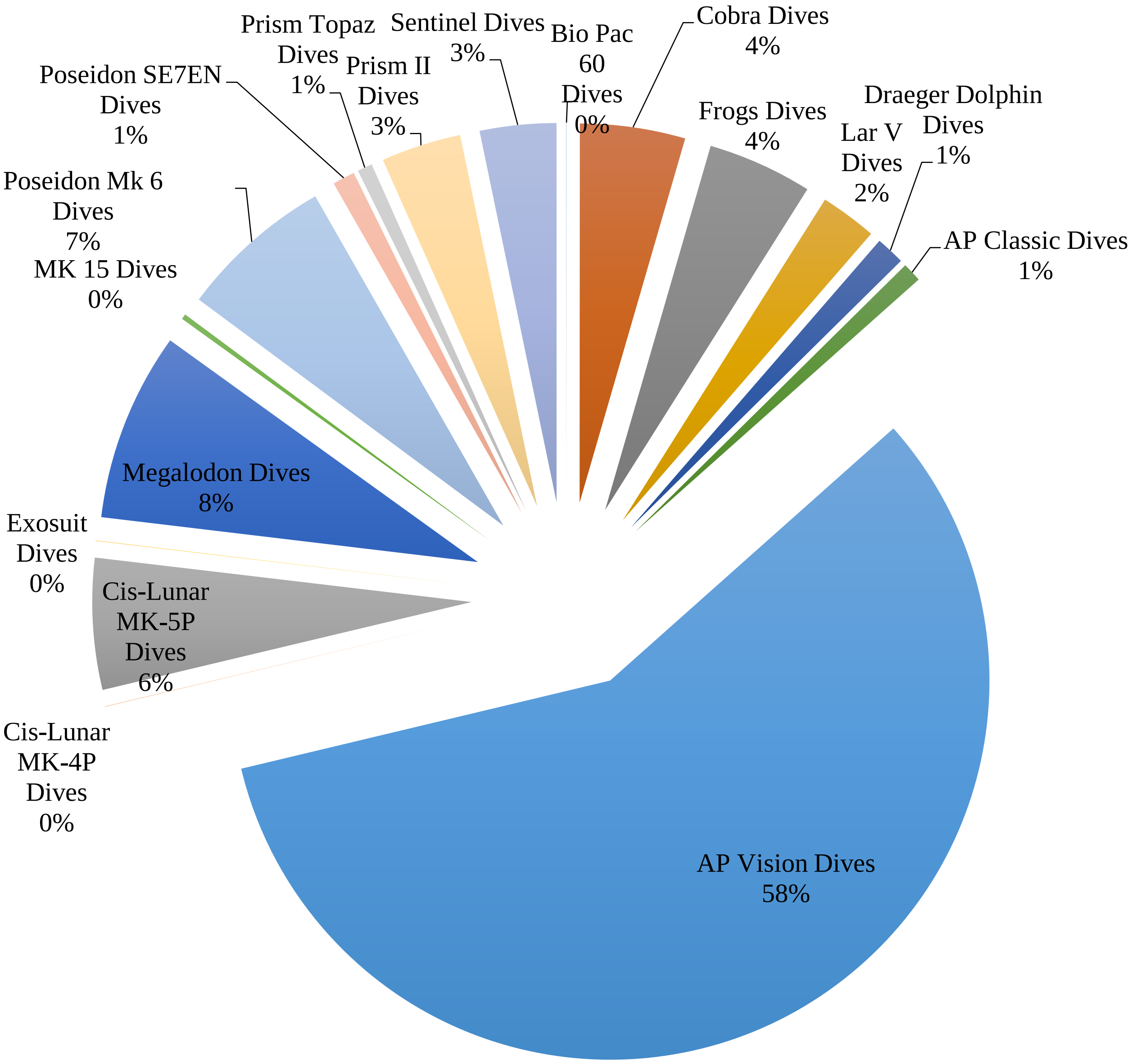


Figure 7. Rebreather use by platform, 1998-2013.

A closer examination of the 1,159 100% oxygen rebreather dives submitted for the sample period finds a nearly equal split for divers using the Cobra (40%) and divers logging dives on the Frogs (39%). The Lar V was used on 21% of the 100% oxygen dives submitted (Figure 8). The Bio Pac 60 dive was indicated to be an experiment. These dives were logged by 17 divers representing four organizations (California Department of Fish and Wildlife, University of California Santa Cruz, University of Connecticut, and University of Hawaii).

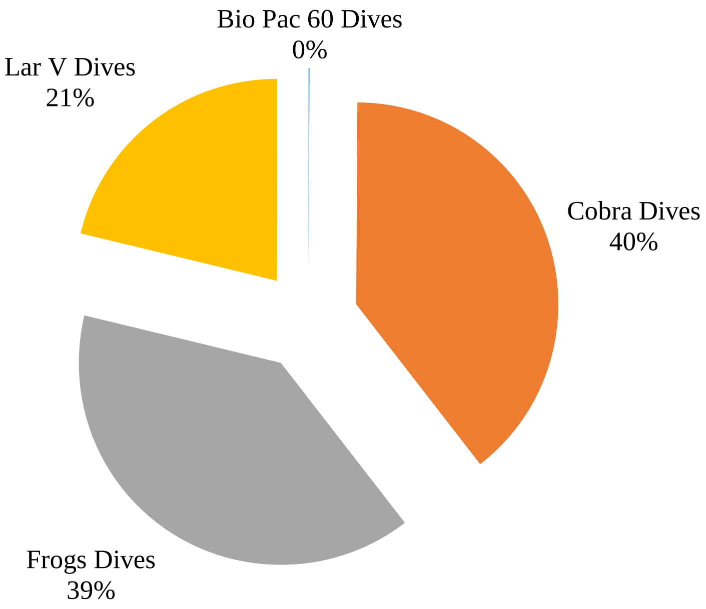


Figure 8. 100% oxygen rebreather dives by platform, 1998-2013.

Excluding the 100% oxygen units and the Exosuit from the CCRs used between 1998 and 2013 leaves 11 rebreather make/models represented: the AP Classic and AP Vision (Inspiration or Evolution), the Cis-Lunar MK-4P, the Cis Lunar MK-5P, the Megalodon, the MK 15, the Poseidon MK6, the Poseidon SE7EN, the Prism Topaz, the Prism II, and the Sentinel (Figure 9).

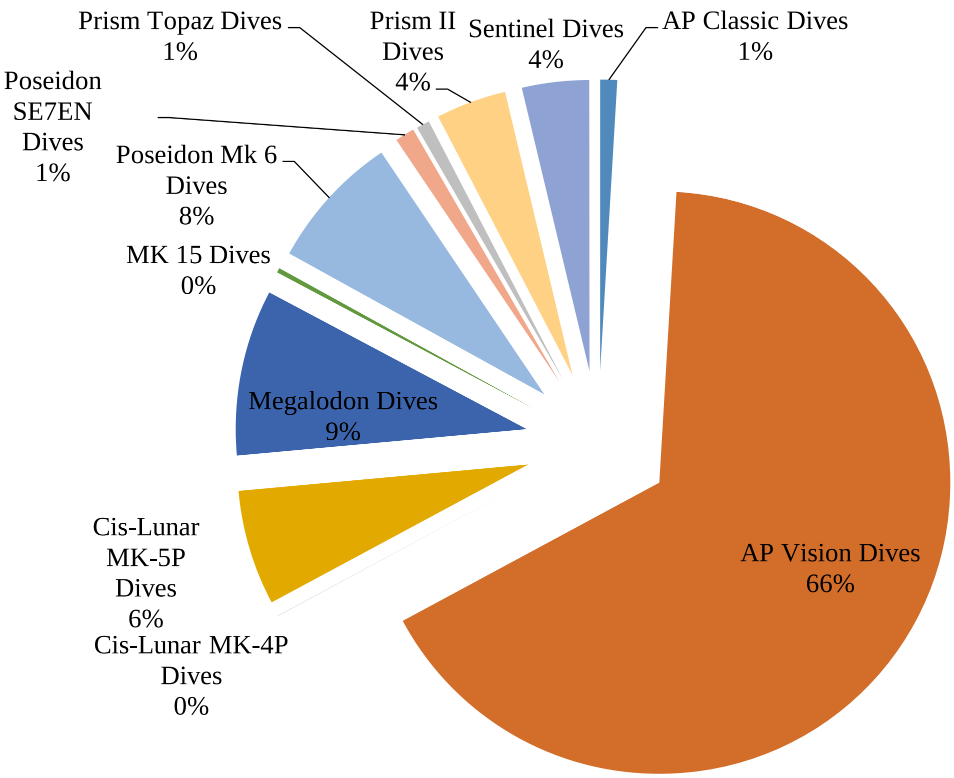


Figure 9. Multi Gas CCR dives by platform, 1998-2013.

A total of 205 divers were recorded logging 8,913 reported CCR dives on these multi gas rebreather platforms. Figure 10 breaks the multi gas rebreather use down by diver percentage. CCR platforms in Figure 10 were collapsed to the manufacturer level for simplicity of tabulation.

Twenty-Six of the 221 divers appearing in this survey logged dives on multiple rebreather platforms (Table 4). The logs indicate that some of these multi-platform dives were probably 'try' dives where the diver was testing a different rebreather model. However, the logs also indicate several of these divers were/are operational on multiple rebreather platforms.

Table 4. Divers Logging Dives on Multiple Platforms

Diver	**Rebreather Platform On Which Dives Were Logged**
0ec02f5a	Poseidon Se7en; Poseidon Mk 6
0ed6755c	AP Vision; Poseidon Mk 6
1dbb29a1	AP Vision; Cis-Lunar MK-5P; Poseidon Se7en; Poseidon Mk 6
8c466cbe	Cis-Lunar MK-5P; Poseidon Se7en; Poseidon Mk 6
a3f4bcfa	Cis-Lunar MK-4P; Cis-Lunar MK-5P; Poseidon Mk 6
a6fe06a0	AP Vision; Cis-Lunar MK-5P; Poseidon Mk 6
b9bf2da6	Cis-Lunar MK-5P; Poseidon Se7en
Bell	AP Vision; Prism II
Boland	Cis-Lunar MK-5P; Megalodon
CM	AP Classic; AP Vision

Conlin	AP Vision; Sentinel
Ed	Exosuit; Sentinel
Flanagan	AP Vision; Draeger Dolphin; Lar V; Poseidon Mk 6
Godfrey	AP Vision; Bio Pac 60; Prism II
Green	AP Classic; Megalodon
Hauk	AP Vision; Megalodon
Hoyt	AP Classic; AP Vision; Megalodon
Keusenkothen	AP Classic; AP Vision
LK	AP Vision; Poseidon Mk 6
McFall	AP Vision; Megalodon
Nunn	AP Vision; Prism II
Pence	AP Vision; Cis-Lunar MK-5P; Draeger Dolphin; Lar V; MK 15; Poseidon Mk 6; Prism II
Rooney	Cis-Lunar MK-5P; MK 15; Megalodon
Sellers	AP Classic; AP Vision; Prism II
Seymour	AP Vision; Prism II; Sentinel
Zgliczynski	AP Vision; Megalodon

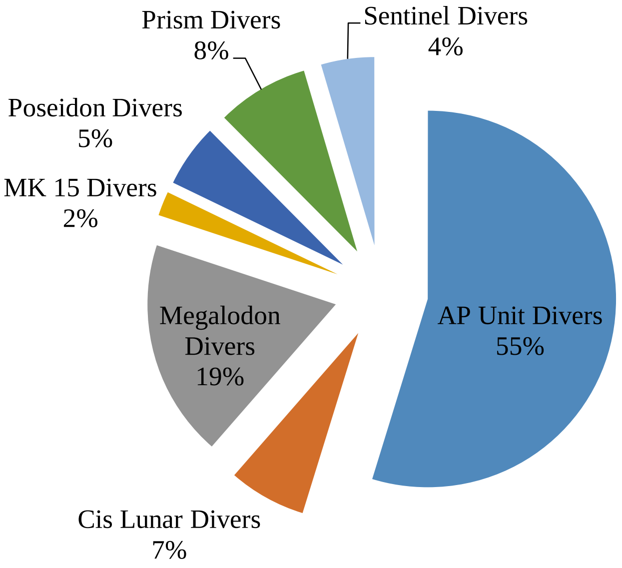


Figure 10. CCR platforms by divers, 1998-2013.

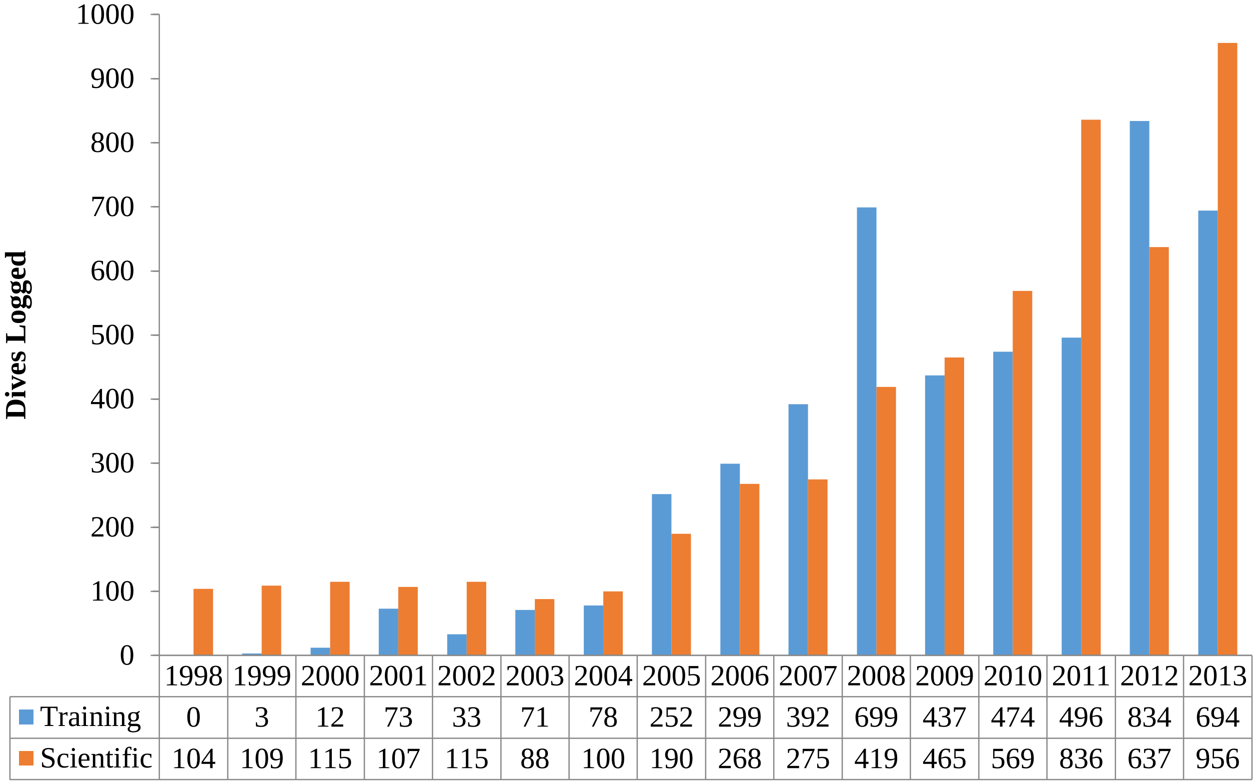
Rebreather Dives by Purpose

Per AAUS reporting criteria dives are categorized as training/proficiency or scientific. Incorporating non-AAUS organizations in the dataset meant not being able to rely on the proficiency classification as one of the criteria for dive purpose, therefore the category was boiled down to training or scientific. During the 16-year review period, the reporting organizations provided 10,200 rebreather logs. Scientific dives accounted for 52% of the dives. Training dives accounted for 48% of the logged dives.

When looking at the divers performing these dives, only 41% of the 221 reported divers recorded scientific dives between 1998 and 2013, while 59% of these divers logged training dives. Annual data show an increase in the number of dives and divers logging rebreather, scientific, and training dives over time (Table 5 and Figures 12-13).

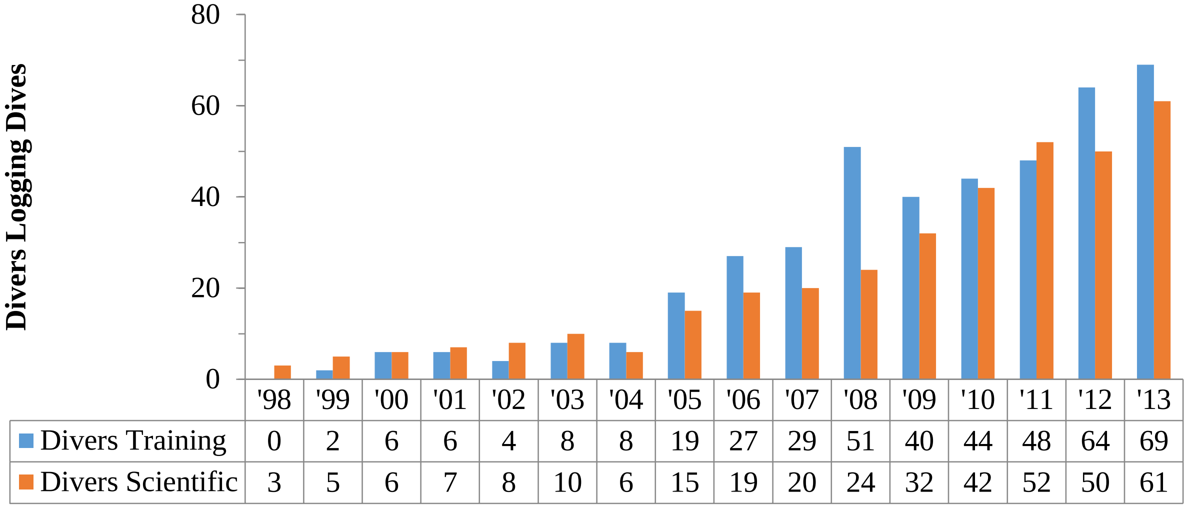
Table 5. Rebreather dives logged by purpose.

	Training Dives Logged	**Training Dive Time (min)**	**Divers Logging Training Dives**	**Scientific Dives Logged**	**Scientific Dive Time (min)**	**Divers Logging Scientific Dives**
1998	0	0	0	104	6,341	3
1999	3	155	2	109	4,114	5
2000	12	568	6	115	6,657	6
2001	73	6,417	6	107	10,469	7
2002	33	2,176	4	115	11,292	8
2003	71	4,812	8	88	3,821	10
2004	78	4,494	8	100	5,277	6
2005	252	16,700	19	190	17,511	15
2006	299	18,381	27	268	20,031	19
2007	392	20,267	29	275	20,608	20
2008	699	27,679	51	419	23,945	24
2009	437	25,504	40	465	31,124	32
2010	474	23,888	44	569	52,511	42
2011	496	33,326	48	836	61,873	52
2012	834	59,637	64	637	53,546	50
2013	694	43,907	69	956	78,908	61
Total	**4,847**	**287,911**	**205**	**5,353**	**408,028**	**140**



	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
🟦 Training	0	3	12	73	33	71	78	252	299	392	699	437	474	496	834	694
🟧 Scientific	104	109	115	107	115	88	100	190	268	275	419	465	569	836	637	956

Figure 11. Training and scientific dives logged by year.



	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13
🟦 Divers Training	0	2	6	6	4	8	8	19	27	29	51	40	44	48	64	69
🟧 Divers Scientific	3	5	6	7	8	10	6	15	19	20	24	32	42	52	50	61

Figure 12. Divers logging training and scientific diving by year.

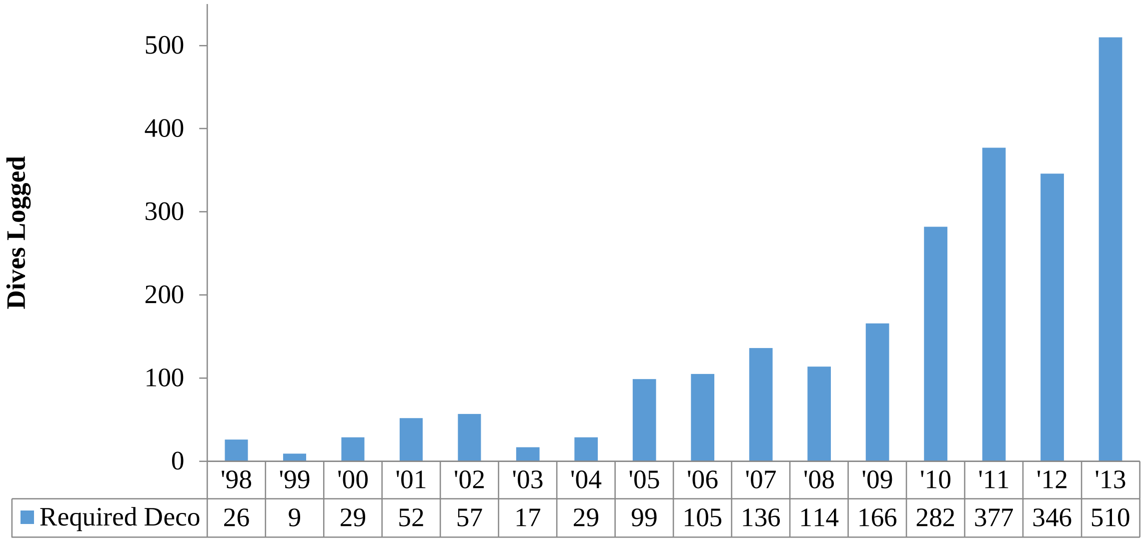
Specialized Diving Environments

Specialized diving environments for this review were defined as dives at altitude, dives conducted with overhead obstruction (water filled caverns or caves), and dives with required decompression stops. These categories were selected because each requires special planning and operational considerations.

Only nine divers from one organization (US National Park Service) logged dives defined as at altitude (dives conducted at an altitude greater than 1000 ft [300 m] above sea level, or dives conducted at altitudes greater than 300 ft [90 m] above sea level when dives exceed 145 fsw [44 msw] actual depths). NPS logged 362 rebreather dives for 18,373 min of dive time between 2006 and 2013.

Eight divers from four organizations (California Academy of Sciences, The Florida Aquarium, the National Park Service, and Woods Hole Oceanographic Institution) logged 74 overhead dives for 8,406 min of dive time. These dives were conducted from 2010 through 2013.

Required decompression is the specialized diving environment with significant numbers of rebreather dives. Of the 10,200 dives logged during the 16-year sample period, 2,354 dives (23%) required decompression. One-hundred of the 221 divers (46%) in the sample logged rebreather dives requiring decompression, totaling 232,252 min of dive time. Fifteen of the 20 organizations, 75%, submitting rebreather logs for the requested sample period logged required decompression dives. Required decompression dives were logged every year of the sample period and increased in frequency almost every year (Figure 13).



	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13
■ Required Deco	26	9	29	52	57	17	29	99	105	136	114	166	282	377	346	510

Figure 13. Dives with required decompression by year.

Full-Face Masks and Mouthpiece Retention Devices

This sample finds very little full-face mask or mouthpiece retention device use. All use reported was full-face mask. Three divers from three organizations (NOAA, NPS, and University of North Carolina at Wilmington) logged 73 dives for 5,099 min of dive time during the 16-year sample period.

Breathing Gas

Analyzing the sample by breathing gas finds 100% oxygen accounted for 11% of the dives conducted (Figure 14 and Table 6). These dives were conveyed by three organizations (California Department of Fish and Wildlife, University of California Santa Cruz, and University of Hawaii) and reported 12 divers logging 1,160 dives for 23,794 min of dive time (Table 4).

Nitrox as the breathing gas in the diver's loop was reported by 18 of 20 organizations (Table 5). A total of 203 divers logged 7,235 dives for 475,383 min of dive time, 71% of the dives logged. Nitrox appeared as the breathing gas to a maximum depth of 171 fsw (52 msw).

Breathing gasses containing helium, defined in this review as mixed gas, were listed for 18% of the dives logged, 1,805 dives, 1,963,762 min of dive time. Fourteen organizations reported 72 divers had logged mixed gas dives between 1998 and 2013.

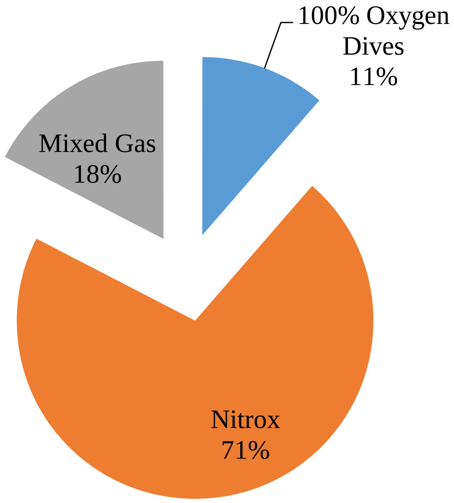


Figure 14. Dives classified by breathing gas used.

Table 6. Breathing gas used for rebreather diving, 1998-2013.

	100% Oxygen Dives	**100% Oxygen Dive Time (min)**	**Divers Logging 100% Oxygen Dives**	**Orgs. Reporting 100% Oxygen Dives**	**Nitrox Dives**	**Nitrox Dive Time (min)**	**Divers Logging Nitrox Dives**	**Orgs. Reporting Nitrox Dives**	**Mixed Gas Dives**	**Mixed Gas Dive Time (min)**	**Divers Logging Mixed Gas Dives**	**Orgs. Reporting Mixed Gas Dives**
1998	64	1,901	1	1	22	1,346	19	8	18	3,094	1	1
1999	66	1,362	1	1	39	2,272	27	9	7	635	2	1
2000	32	647	2	2	78	4,652	41	13	17	1,926	3	1
2001	39	1,729	4	2	100	8,833	56	13	41	6,324	6	2
2002	40	910	1	1	55	3,132	35	10	53	9,426	6	2
2003	10	170	1	1	148	8,356	61	13	1	107	1	1
2004	38	688	1	1	130	7,286	55	12	10	1,797	2	2
2005	49	1,065	3	2	323	23,122	93	15	70	1,0024	9	2
2006	65	1,380	2	1	424	26,682	106	16	78	10,350	11	4
2007	70	1,336	3	2	516	27,831	126	16	81	11,708	10	5
2008	223	3,639	7	2	866	44,371	115	15	29	3,614	7	4
2009	154	3,157	6	2	631	40,846	112	15	117	12,625	12	6
2010	183	3,098	8	3	665	49,094	122	14	207	24,207	22	6
2011	37	784	4	1	1,015	66,642	147	17	280	27,773	27	9
2012	58	1,181	3	1	1,080	80,794	152	17	333	31,208	22	9
2013	32	747	3	1	1,155	80,124	158	16	463	41,944	31	11
Totals:	1,160	2,3794	12	3	7,235	475,383	203	18	1805	196,762	72	14

Table 7. 100% oxygen use by reporting organizations, 1998-2013.

	1998	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**Divers**
CDWF								■		■	■	■	■	■	■	■	**6**
UCSC	■	■	■	■	■	■	■	■	■	■	■	■	■				**3**
UH			■	■									■				**3**

CDWF = California Department of Fish and Wildlife; UCSC = University of California Santa Cruz; UH = University of Hawaii

Table 8. Nitrox use by reporting organizations, 1998-2013.

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Divers
BM/AME	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	11
CAS											■	■	■	■	■	■	5
ECU								■	■	■	■	■	■		■	■	14
FLAQ													■	■	■	■	3
HDAR									■	■	■	■	■				6
IMS Eilat													■	■	■	■	19
NOAA															■	■	21
NPS								■	■	■	■	■	■	■	■	■	15
NURC									■	■	■						24
Ol Miss									■		■	■	■	■			1
SCRIPPS						■	■	■	■						■	■	6
UC Davis						■	■										5
UCONN							■		■	■	■	■	■	■	■	■	9
UH		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	51
UNCW									■			■	■				8
UNH									■	■	■	■	■	■	■		3
URI																■	2
WHOI														■	■	■	9
■	= Diving Activity																

BM/AME = Bishop Museum/Association for Marine Exploration
CAS = California Academy of Sciences
ECU = East Carolina University
FLAQ = The Florida Aquarium
HDAR = Hawaii Division of Aquatic Resources
IMS Eilat = The Interuniversity Institute for Marine Sciences in Eilat
NOAA = National Oceanic and Atmospheric Administration
NPS = National Park Service
NURC = National Undersea Research Center
Ol Miss = University of Mississippi
SCRIPPS = Scripps Institute of Oceanography
UC Davis = University of California Davis
UCONN = University of Connecticut
UH = University of Hawaii
UNCW = University of North Carolina at Wilmington
UNH = The University of New Hampshire
URI = University of Rhode Island
WHOI = Woods Hole Oceanographic Institution

Table 9. Mixed gas activity of the organizations reporting 1998-2013

	1998	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**Divers**
BM/AME	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	**13**
CAS												🟩	🟩		🟩	🟩	**4**
ECU										🟩				🟩		🟩	**4**
FLAQ														🟩	🟩	🟩	**3**
HDAR											🟩		🟩				**3**
IMS Eilat													🟩	🟩	🟩	🟩	**7**
NOAA															🟩	🟩	**10**
NPS									🟩	🟩							**2**
Ol Miss												🟩		🟩	🟩	🟩	**1**
UCONN									🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	**4**
UH				🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	**14**
UNCW													🟩	🟩			**6**
UNH												🟩		🟩	🟩	🟩	**3**
WHOI																🟩	**2**

- BM/AME = Bishop Museum/Association for Marine Exploration
- CAS = California Academy of Sciences
- ECU = East Carolina University
- FLAQ = The Florida Aquarium
- HDAR = Hawaii Division of Aquatic Resources
- IMS Eilat = The Interuniversity Institute for Marine Sciences in Eilat
- NOAA = National Oceanic and Atmospheric Administration
- NPS = National Park Service
- Ol Miss = University of Mississippi
- UCONN = University of Connecticut
- UH = University of Hawaii
- UNCW = University of North Carolina at Wilmington
- UNH = The University of New Hampshire
- WHOI = Woods Hole Oceanographic Institution

Rebreather Dives by Depth Profile

AAUS depth profile designations were used to classify dives by depth. They are:

- 0-30 ft (0-9 m)
- 31-60 ft (>9-18 m)
- 61-100 ft (>18-30 m)
- 101-130 ft (>30-40 m)
- 131-150 ft (>40-46 m)
- 151-190 ft (>46-58 m)
- 191 ft -> (>58 m)

While useful for comparing rebreather dives to the database of other modes of diving within AAUS, the number of dives deeper than 190 fsw (58 msw) and the range of depths logged indicate a need to rework this scale for deeper rebreather dives. No attempt to rework the depth comparison scale was made for this review.

Many divers and organizations started looking at rebreathers, outside of 100% oxygen units, for the advantages they bring for deeper diving. The depths at which rebreathers are being used are evidence that they are becoming the diving mode of choice for deeper excursions made within the scientific diving community. However, the numbers also indicate they are finding an increasing niche in the shallower depths among scientific rebreather divers.

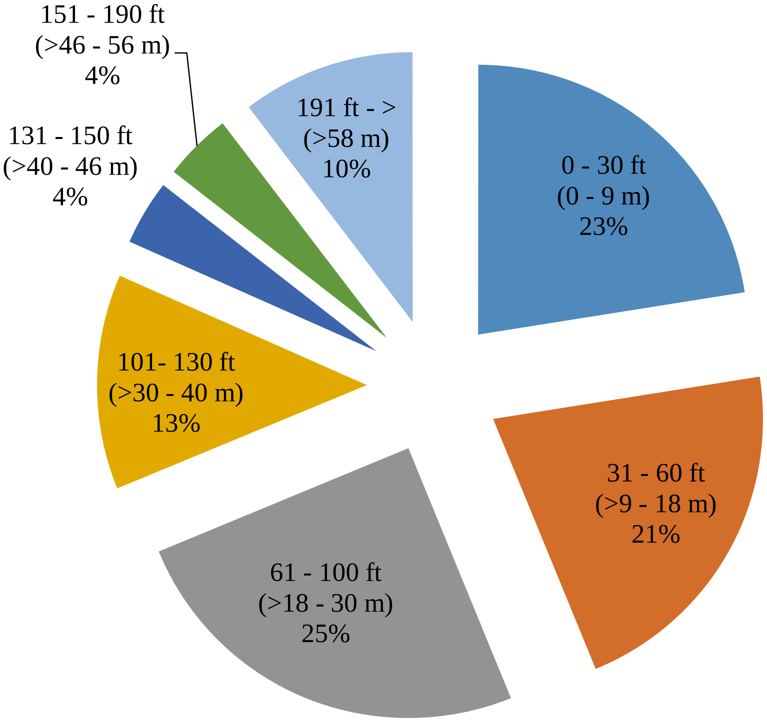


Figure 15. Dives logged by depth profile - includes oxygen, semiclosed and closed-circuit rebreathers, 1998-2013.

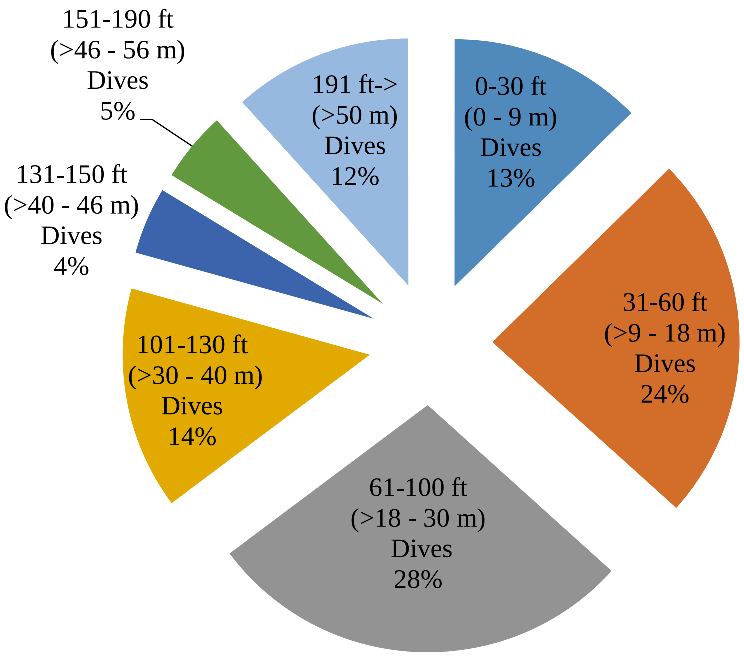


Figure 16. Dives by depth profile, excluding 100% oxygen units, 1998-2013.

Isolating 100% oxygen dives in the depth profile data changes the percentage distribution slightly. It also identifies approximately 1% of the 100% oxygen dives being logged with a maximum depth greater than 30 fsw (9 msw). The maximum depth logged on a 100% oxygen rebreather was 52 fsw (16 msw). The 11 dives were (depth [fsw]/min surface to surface): 33/27, 34/37, 52/17, 45/15, 43/12, 40/12, 45/17, 35/11, 34/16, 45/12, and 32/15. The dive task (surface sea otter capture) suggests that time at depth was minimal. However, it was interesting to find documented PO_2 exposures as high as 2.58 ATA.

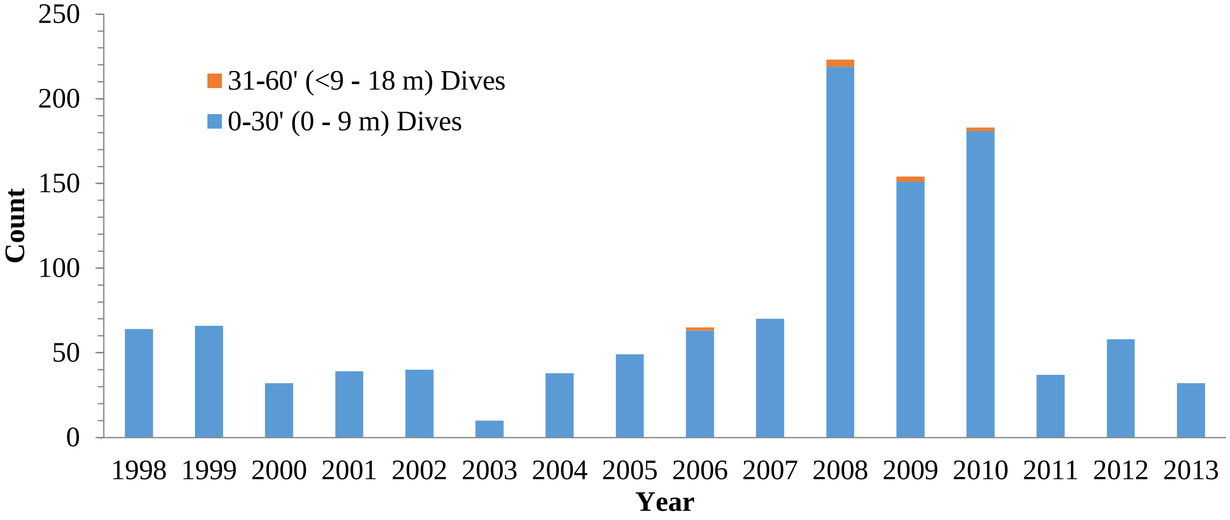


Figure 17. Oxygen rebreather dives by depth range, 1998-2013.

To try and identify a trend in deeper work within the community, the data from AAUS OMs reporting rebreather dives in the 191 fsw (58 msw) and greater depth range was compared to the 191 fsw and greater depth reports in the AAUS statistical database. The AAUS dives by depth range reports do not break the dives down by diving mode, so to get the comparison the rebreather dives reported for this review were subtracted from the AAUS totals for this depth category. All organizations reporting to AAUS for this depth range are included and provide the basis for the open-circuit portion of the graph. Only data from organizations providing dives for this study that are common to the AAUS database were used to provide the CCR portion of Fig 18. The comparison found rebreather use for dives greater than 190 ft (58 m) was not reported in the AAUS community prior to 2001. Since that time rebreather use in these depth ranges has increased, while OC dives beyond 190 fsw have decreased within the AAUS community. It is possible that other AAUS CCR users not providing dives for this study would further impact the OC vs CCR relationship.

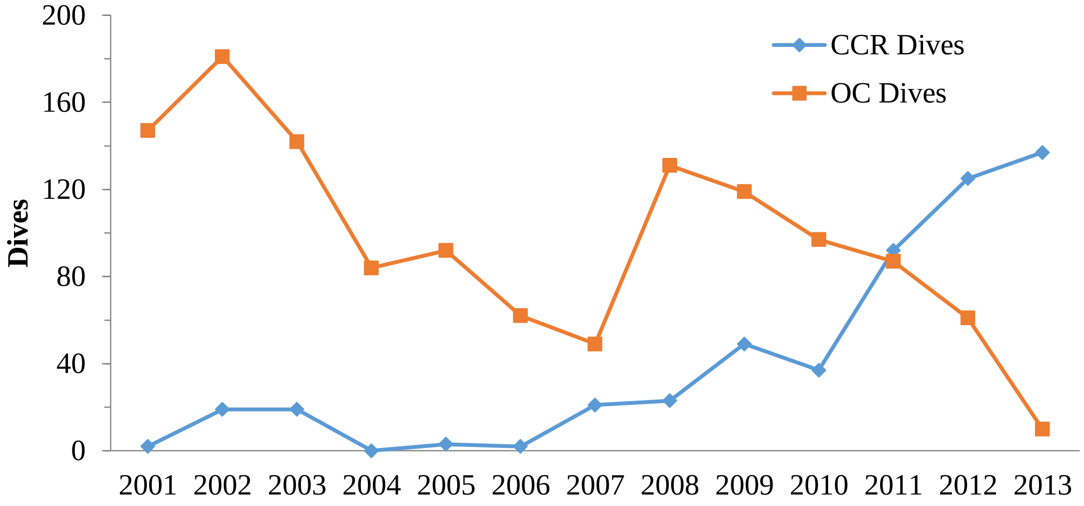


Figure 18. AAUS Dives ≥191 ft (58 m) and > OC vs CCR, 2001-2013.

There were 1060 dives reported in the ≥191 ft (58 m) depth category during the 16 years of the study period. Accounting for all rebreather logs supplied for the review there were 1,390 dives logged beyond 190 fsw. The deepest dives reported were to 486 fsw (148 msw, 15.7 ATA). To better understand the distribution of these dives, they were classified by pressure range.

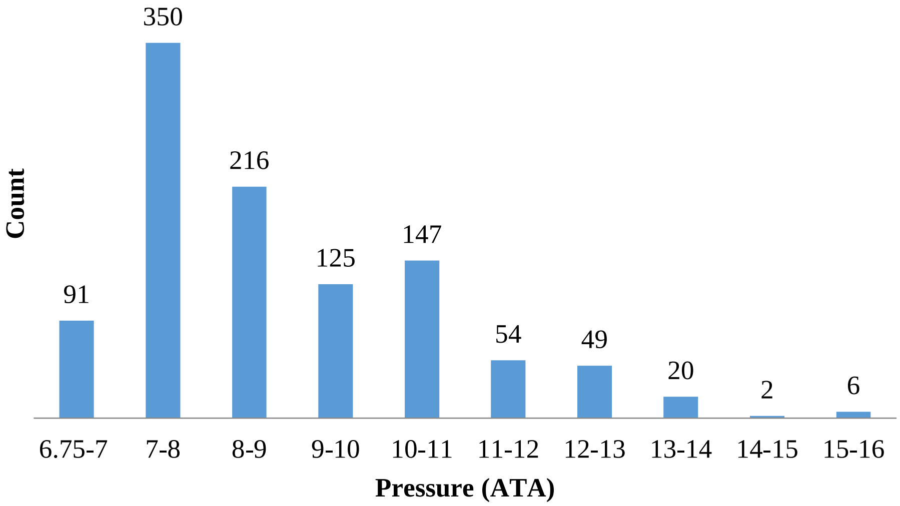


Figure 19. Rebreather dives ≥191 ft (58 m) by pressure range, 1998-2013.

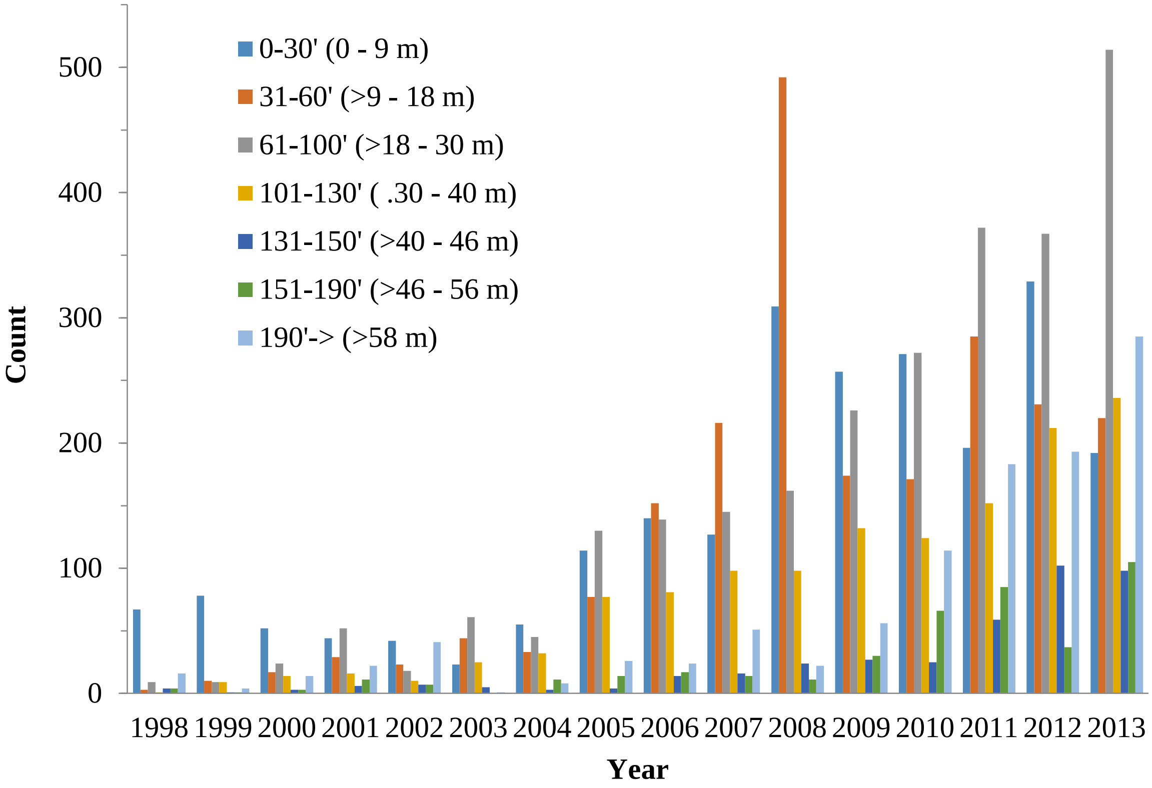


Figure 20. Annual dives by depth range, all rebreather types and breathing gas, 1998-2013.

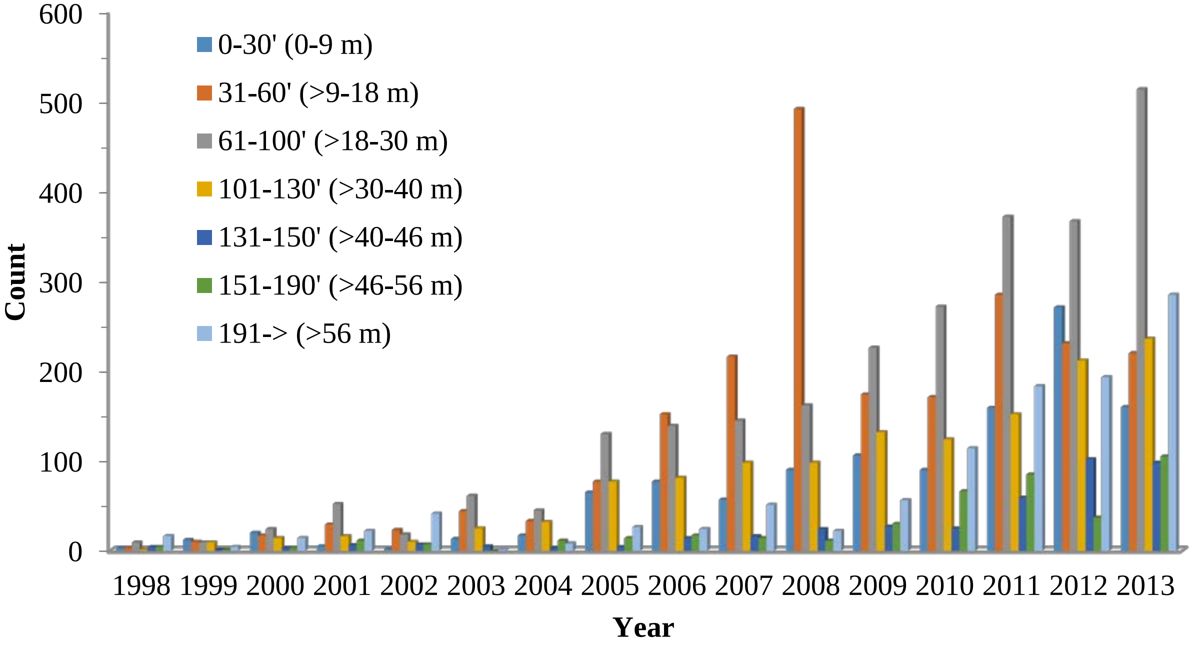


Figure 21. Annual dives by depth range (excluding 100% oxygen dives), 1998-2013.

Table10. Rebreather dives by AAUS depth profile, all rebreather types, 1998-2013.

	0-30	**0-30 Time**	**31-60**	**31-60 Time**	**61-100**	**61-100 Time**	**101-130**	**101-130 Time**	**131-150**	**131-150 Time**	**151-190**	**151-190 Time**	**190->**	**190-> Time**
1998	67	1,983	3	159	9	537	1	114	4	273	4	299	16	2,976
1999	78	2,001	10	452	9	559	9	583	1	95	1	117	4	462
2000	52	1,477	17	893	24	1,623	14	881	3	425	3	204	14	1,722
2001	44	2,141	29	3,114	52	4,591	16	969	6	673	11	1,284	22	4,114
2002	42	968	23	1,216	18	1,132	10	531	7	605	7	889	41	8,127
2003	23	751	44	2,242	61	3,360	25	1,649	5	524	0	0	1	107
2004	55	1,518	33	1,895	45	2,507	32	1,879	3	260	11	194	8	1,518
2005	114	4,463	77	5,208	130	1,1214	77	5,690	4	292	14	1,207	26	6,137
2006	140	6315	152	8,513	139	9,704	81	5,548	14	1,014	17	1,500	24	5,818
2007	127	3,720	216	9,560	145	10,095	98	5,498	16	1,445	14	1,561	51	8,996
2008	309	8,124	492	18,111	162	12,069	98	7,335	24	2,366	11	715	22	2,904
2009	257	7,958	174	11,660	226	15,787	132	9,024	27	2,046	30	2,404	56	7,749
2010	271	7,691	171	11,177	272	23,779	124	9,747	25	2,586	66	6,880	114	14,539
2011	196	9,673	285	19,201	372	26,405	152	9,770	59	3,288	85	6,105	183	20,757
2012	329	21,621	231	14,920	367	30,449	212	15,537	102	5,589	37	2,862	193	22,205
2013	192	8,436	220	14,518	514	40,619	236	17,382	98	5,085	105	8,629	285	28,146
Total	**2,296**	**88,840**	**2,177**	**122,839**	**2,545**	**194,430**	**1,317**	**92,137**	**398**	**26,566**	**416**	**34,850**	**1,060**	**136,277**

Table 11. Rebreather dives by depth profile, all rebreather types, 1998-2013.

Year	Divers Logging Dives 0-30	Orgs. Reporting 0-30 Dives	Divers Logging Dives 31-60	Orgs. Reporting 31-60 Dives	Divers Logging Dives 61-100	Orgs. Reporting 61-100 Dives	Divers Logging Dives 101-130	Orgs. Reporting 101-130 Dives	Divers Logging Dives 131-150	Orgs. Reporting 131-150 Dives	Divers Logging Dives 151-190	Orgs. Reporting 151-190 Dives	Divers Logging Dives 190->	Orgs. Reporting 190-> Dives
1998	2	2	1	1	2	1	1	1	1	1	1	1	1	1
1999	6	3	2	1	2	2	1	1	1	1	1	1	2	1
2000	9	3	4	2	3	2	3	1	3	2	2	1	3	1
2001	6	3	8	2	8	2	6	2	3	2	3	2	6	2
2002	3	3	3	2	6	2	5	2	5	2	5	2	7	2
2003	6	4	11	4	11	4	8	3	3	2	0	0	1	1
2004	8	5	7	3	10	4	5	3	2	2	1	1	1	1
2005	17	7	16	4	16	5	8	3	4	1	6	2	4	2
2006	20	9	24	11	23	10	22	8	6	4	7	3	6	3
2007	13	6	25	7	23	7	21	7	7	4	7	5	8	4
2008	19	10	44	10	22	7	23	6	10	4	4	3	6	2
2009	24	9	35	10	40	10	32	8	13	5	10	4	9	4
2010	27	9	37	11	40	10	37	10	16	7	18	5	19	6
2011	42	12	43	11	44	11	34	9	28	8	19	7	24	8
2012	57	12	52	12	61	13	51	11	32	10	18	9	21	10
2013	58	13	54	10	72	11	55	10	28	9	33	11	27	10
Total	**157**	**19**	**199**	**18**	**176**	**16**	**147**	**16**	**92**	**15**	**66**	**14**	**72**	**14**

Conclusions

Although still small in number of divers and total dives logged when compared to open-circuit, rebreather diving in the scientific diving community is growing. The advantages of extended bottom time, the virtual elimination of the limited gas supply pressure compared to open-circuit, improved productivity resulting from reduced surface interval requirements and the rebreather diver's ability to breathe the "best mix" throughout the water column compared to open-circuit divers on similar dive profiles, and the elimination of bubbles are just some of the examples expressed of why rebreathers are becoming more prevalent in the community.

The study indicates a trend toward increasing numbers of rebreather dives and rebreather divers within the scientific diving community.

Acknowledgments

The author acknowledges the time and effort of the individuals compiling and submitting dive logs for this review. Without their assistance in obtaining and in some cases decoding these records, this work would not have been possible.

References

US Navy Diving Manual, Volume 2, Revision 6. NAVSEA 0910-LP-106-0957. Naval Sea Systems Command: Washington, DC, 2008.

QUESTIONS AND DISCUSSION

DAVID KUSHNER: Steve, just one question. Did you split up, by chance, the depth distributions of the dives between training and working dives?

STEVE SELLERS: I did not, but I can.

DAVID KUSHNER: I am interested to see if there is any difference there.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

Rebreather Evolution in the Foreseeable Future

Richard L. Pyle

Ichthyology, Bishop Museum, 1525 Bernice Street, Honolulu, HI 96744, USA
deepreef@bishopmuseum.org

Abstract

Although modern rebreathers have been in existence for more than 130 years, they have rapidly gained broader use by professional and recreational dives during the past one to two decades. This has been driven largely through advancements in microprocessor design and associated reduction in cost. Current emerging technological developments include real-time oxygen sensor validation, improved carbon dioxide sensors, automated pre-dive checklists, and improved information access through more advanced head-up display systems. The key next steps in rebreather technology development are likely to include broader incorporation of non-galvanic oxygen sensors, options for closed-circuit bailout for more effective decompression and diving in physical overhead environments, more robust logging and aggregation of dive data to improve overall rebreather performance and safety, better use of such data for system analysis in real time, and the potential to integrate rebreather diver operation with semi-autonomous underwater robotics. The important trends made possible by these technological advancements will lead to less expensive and more reliable rebreathers, increased safety, and increased operational efficiency and effectiveness.

Keywords: rebreather, technology, sensors, data, bailout, validation

Introduction

During most of the 130-year history of modern rebreathers, they were used primarily for commercial and military purposes (Davis 1955; Quick 1970); up until the 1960s, very little had changed in terms of basic rebreather technology. In his review of the history of rebreather technology, Menduno (2014) described a series of technological "inflection points" that have occurred during the past five decades, representing major shifts in the design and implementation of rebreathers. The first of these was marked by the incorporation of electronic oxygen sensors by Alan Krasberg in 1962, followed by the development of the "Electrolung" by Walter Starck (Tzimoulis 1970; Starck and Starck 1972; Starck 1993). These early efforts led to a series of electronically controlled mixed-gas rebreathers developed by Biomarine Industries, Carleton Technology, General Electric, Divematics, Westinghouse, Sterling Electronics, and Normalair-Garrett; some of which were used for scientific purposes during the 1970s and early 1980s (Collette and Earle 1972; Hanlon et al. 1982; Collette 1996).

The next inflection point in rebreather technological development coincided with the dawn of "Technical Diving" in the mid to late 1980s (Hamilton 1990). The development and testing of the of the Cis-Lunar MK-I "Failsafe Rebreather for Exploration Diving" (FRED) during the Wakulla Springs Project (Stone 1989; 1990) was one of the first major steps in this "second wave" of modern rebreather technology. This was followed closely by the use of semiclosed rebreathers by Olivier Isler to explore caves in Europe (Isler 1990; 1992; 1993); efforts to explore the Blue Holes of Andros Island using rebreathers by Stuart Clough, Rob Parker and Kevin Gurr (Palmer 1990); and the use of rebreathers to film marine life by Howard Hall and Bob Cranston (Hall 1990). Over the course of the next two decades, rebreather use expanded dramatically, with several manufacturers producing units targeted at the technical diving community. The first two "Rebreather Forums" (Menduno 1994; Richardson et al. 1996) played a vital role in establishing standards for training and testing, and brought the technical diving community together to focus on improving rebreather safety, as well as expanding the application of rebreathers to a broader array of users (Pyle 1996a). This included the use of rebreathers for exploration of deep coral-reef habitats (Pyle 1996b; 1998; 1999; 2000; Pence and Pyle 2002, Parrish and Pyle 2002; Sherman et al. 2009; Sieber and Pyle 2010; Rowley 2014), and for conducting research where stealth and low acoustic signatures are critical (Lobel 2001; 2005; Tomoleoni 2012; Lindfield et al. 2014).

We are now at the third major inflection point for rebreather technological development, most visibly represented by the highly successful "Rebreather Forum 3" (Vann et al. 2014). This inflection point is characterized by the emergence of rebreather designs targeted at recreational (non-technical) divers, with a strong emphasis on reduced operational complexity and training, lower cost, and improved overall safety. The last of these is of critical importance for the transition of rebreathers into the recreational diving market, as preliminary data drawn from the technical diving community suggests that rebreather divers suffer from considerably higher rates of incidents than general open-circuit recreational diving (Fock 2014).

Innovation and technological advancement were among the core themes of Rebreather Forum 3 (Richardson and Vann 2014), and the trend towards wide-scale adoption of rebreathers by non-technical divers is going to be driven primarily by such technological advancements (Stone 2014). Not only does this impact the recreational diving community, but the scientific diving community is likewise poised to expand the use of rebreathers over the next few years (McDonald and Lang 2014; Pyle et al. 2016). This article summarizes some of the key technologies that are currently emerging in modern rebreather designs, as well as those that are likely to emerge in the coming years; particular with regard to how these advancements impact the use of rebreathers by scientific divers.

Emerging Technologies

Throughout the history of rebreather development, not all technological advancements were widely adopted. For example, the development of a cryogenic rebreather held great promise, but was never fully developed (Kushman 1969). Carbon dioxide (CO_2) absorbent canisters designed with a special hydrophobic membrane system to keep the absorbent material dry without significantly impacting the work of breathing were extremely effective (Nordstrom 1993), but were never widely adopted; in part due to cost. Other technologies that have been used with experimental rebreathers more than a decade ago were ahead of their time, but technological advancements have now made them more economical and feasible to implement. Three such examples include active oxygen sensor validation, CO_2 monitoring, and information-rich head-up displays.

Oxygen sensor validation

Perhaps the most critical factor for ensuring safe operation of closed-circuit rebreathers is accurate oxygen monitoring and control. Preliminary analysis suggests that the leading cause of fatalities for recreational rebreathers (when data are available to infer a cause) is hypoxia (17%), with hyperoxia assumed in an additional 4% of cases (Fock 2014). If these numbers are extrapolated to the 31% of fatalities with scant data, then perhaps 30% of all rebreather fatalities involve too much or too little oxygen.

The standard approach to ensuring reliable oxygen readings in closed-circuit rebreathers is the incorporation of three oxygen sensors. This general approach not only incorporates a form of "triple-redundancy," but also provides an opportunity for "voting logic," whereby an inaccurate reading of one sensor can be recognized as an outlier based on the readings of the other two. However, a careful analysis of this approach for inferring reliable oxygen concentrations in rebreather gas mixtures calls its efficacy into question. In an excellent review of the topic, Jones (2014) showed how the reliability of three-sensor voting systems is much lower than popular perception, due largely to the lack of adequate statistical independence of the three individual sensor readings, and the fact that most voting logic systems do not take "asymmetrical outcomes" (i.e., different implications of erroneous oxygen partial pressure [PO_2] readings depending on the depth) of failures into account.

One example of a situation in which voting logic fails is when two of the three sensors read similar but incorrect values, while the third sensor is correct but significantly different from the other two. I have experienced this situation on at least three separate occasions during my time diving with Cis-Lunar MK-IV and MK-5P rebreathers, one of which is reported by Jones (2014). In all three cases, condensation on the oxygen sensors had apparently trapped a small pocket of gas against the sensor membrane, causing the sensors to indicate a PO_2 that was not consistent with the PO_2 in the breathing gas. This represents only one example of many in which oxygen sensors can provide inaccurate readings in such a way that simple voting logic can yield an incorrect PO_2 value.

In these (and other) examples of failed voting logic, I was able to determine the error by examining the behavior of the oxygen sensors readings over time. Specifically, the two incorrect readings tended to be very static, with little or no fluctuation in reading over time. By contrast, the one correct reading was dynamic, and was more responsive to small gas injections to the loop, depth changes, and small fluctuations in the oxygen concentrations resulting from turbulent gas flow and heterogeneous gas mixtures. These observations led to the development of algorithms to monitor oxygen sensor behavior through the rebreather computer control system to much more accurately and reliably determine the reliability of oxygen sensor readings. This approach to determining the reliability of oxygen sensors based on patterns of sensor response to external conditions and parameters is known as "passive sensor validation" (PSV).

There are many ways to incorporate PSV into rebreather control logic, to allow far more reliable determination of sensor reading integrity than simple voting logic based on calibrated PO_2 or millivolt (mV) readings from the sensors. The degree to which sensor values fluctuate – not only in response to ambient conditions such as depth and temperature, but also in comparison to other sensors in the system – can provide important information about which sensor values should be trusted, and which should not. When combined with a large dataset of real-world logged dive data, and taking into account the implications of asymmetrical outcomes, the algorithms can be fine-tuned so as to more accurately determine the confidence of any particular sensor in real time. Although PSV represents a significant improvement over simple voting logic in determining reliable oxygen sensor readings, it is still subject to issues related to statistical independence of components in the system. More proactive approaches to validating oxygen sensor readings can improve reliability of interpreted PO_2 further still.

By the late 1980s, Cis-Lunar Development Laboratories had developed a feature for their MK-III rebreather whereby a diver could press a valve on the gas manifold to inject diluent gas directly on the face of the oxygen sensors. The initial impetus for this feature was a method for removing any condensation that may have accumulated on the sensor membranes. However, it soon became obvious that the feature provided another, perhaps more important capability: to actively validate the oxygen sensor reading using only a small amount of diluent gas. The basic concept is that if both the depth and the oxygen fraction (FO_2) of the diluent mixture are known, then the oxygen sensors can be validated by exposing them directly to diluent gas and observing the resulting sensor response (either as mV readings, or as calibrated PO_2 readings). By the time the Cis-Lunar MK-5P was produced, it included a feature on the primary computer display that showed the "diluent PO_2" value for the selected diluent gas at the current depth, which allowed the diver to quickly and easily determine which of the three oxygen sensors was responding accurately by injecting a tiny amount of diluent directly onto the sensor membranes (Pyle 1997). The original purpose for this feature (purging condensate from the sensors) is still fulfilled, although care in the design of the injection nozzles is important to prevent forcing condensate through the sensor membrane and into the sensor itself.

During an expedition to Fiji in 2002, I began early efforts to design an automatic validation system, whereby the rebreather control system computer would periodically inject gas on the oxygen sensors (either simultaneously or sequentially) and determine the viability of the sensor response with greater precision and accuracy than a human diver could. A few years later, the concept was further developed and tested during the early development of what became the Poseidon/Cis-Lunar MK-VI rebreather (Sieber et al. 2008; Pyle et al. 2009; Sieber et al. 2009; Stone and Pyle 2009; Sieber 2014). This system, which has undergone extensive refinement and adjustment in response to thousands of hours of test diving under a variety of real-world diving conditions, is referred to as "Active Sensor Validation" (ASV).

The ASV system as implemented in modern rebreathers is now far more sophisticated than it was as manually implemented in the Cis-Lunar MK-5P. The basic concept for ASV as implemented in the Poseidon line of rebreathers is described in Pyle et al. (2009), but it involves much more than simply comparing the final PO_2 value from the sensor to the PO_2 of the diluent at the current depth. As implemented in the Poseidon line of rebreathers (Stone and Pyle 2009; Poseidon Diving Systems 2014), the computer injects either oxygen or diluent (depending on a variety of factors) directly on to a single, primary oxygen sensor automatically at intervals of every five minutes during a dive. Taking into account a number of different variables (e.g., current depth, FO_2 of the injected gas, duration of gas injection, ambient temperature, and certain parameters established when the sensor was calibrated prior to each dive, etc.), the algorithm makes a prediction of how the sensor should respond to the gas injection over a period of several seconds after the gas is injected. It then injects the gas and logs the actual sensor response. It then performs a series of tests that compare the predicted response to the actual response, and derives a confidence level that the sensor is performing correctly.

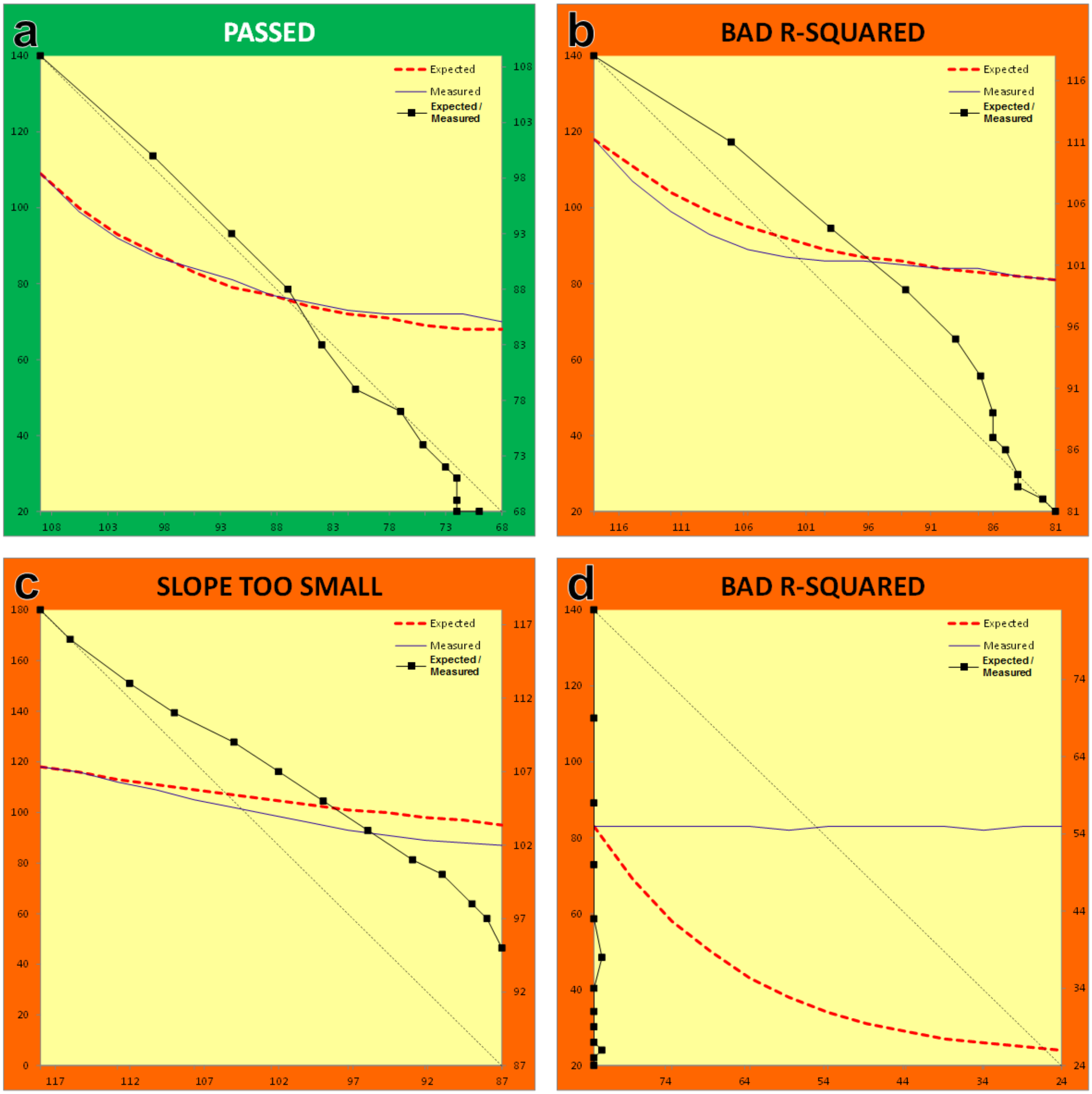


Figure 1. Example data from active sensor validations (ASVs). In all four graphs, the red dashed line represents the predicted response of the sensor (plotted against the PO_2 in centibar on the left y-axis, and unlabeled time on the x-axis); the thin solid blue line represents the actual (logged) measured response of the sensor (against the same two axes); the black line with square data-points represents the ratio of expected (right y-axis) vs measured (bottom x-axis) PO_2 values at regular intervals during the sensor response (as a function of the same unlabeled time period), and the thin dashed diagonal black line represents what a perfect agreement between expected and measured values. Green borders represent a passed validation, and orange borders represent failed validations. The four panels represent a typical response for a functioning, reliable sensor (a), an example where the validation failed because the ratio of expected vs measured values was non-linear (b), an example where the validation failed because the slope of the response curve deviated from the expected value even though

the response was linear (c), and an example of a validation that failed because the sensor was non-responsive (d).

Figure 1 shows example data from four separate sensor validations, one of which passed, and three of which failed. In Figure 1a, the measured response of the sensor (thin blue line) very closely fits the expected response (red dashed line), as indicated by the black data points falling close to the expected 1:1 ratio between expected and measured values. The other three examples show some of the different ways in which measured values might deviate from expected values, resulting in a failed sensor validation test. In Figure 1b, the end value of the measured PO_2 is very close to the end value of the expected PO_2 (far right side of graph), so using only the end-value (as was done manually in the MK-5P validation system) would incorrectly suggest that the sensor was reliable. The example shown in Figure 1c could be due to several factors, such as incorrect temperature readings, incorrect recording of the FO_2 of the diluent gas, or a bad oxygen sensor. The example shown Figure 1d could be caused by several different factors, including condensation on the oxygen sensor, a failed oxygen sensor, a failed solenoid valve, or empty validation gas supply. These graphs depicted in Figure 1 represent only a few of many possible reasons why oxygen sensors might fail ASV, and many of these failures would not be detected using a simple voting logic system.

A similar test can be applied to another aspect of galvanic oxygen sensors that can render them unreliable in certain conditions. The oxygen sensors for most rebreathers are calibrated at the surface using air or 100% oxygen. This means that the sensors are calibrated to have a linear response (i.e., the relationship between the mV and interpreted PO_2 is consistent and linear) only up to a PO_2 of 1.0 bar. However, most rebreather divers select a PO_2 setpoint higher than 1 bar (e.g., 1.2-1.4 bar), so the oxygen control system is normally operating at a range outside the value for which the oxygen sensor is known to be linear. Galvanic oxygen sensors can become "current-limited," whereby the impedance within the sensor can change as the anode is consumed over the life of the sensor, and therefore the maximum current output (and, hence, the maximum voltage) may result in non-linear sensor response at higher PO_2 values (Sieber 2014). If this current-limiting effect happens when the oxygen concentration is in the range of 1.0-1.4 bar, the oxygen sensor may fail to represent the PO_2 value accurately. In such circumstances, the actual PO_2 may be considerably higher than the value interpreted from a current-limited sensor.

To safeguard against this problem, a few rebreather divers confirm the linearity of the sensors at higher PO_2 values (e.g., 1.6 bar) by exposing the sensor to pure oxygen at >1 bar inside a small chamber or "pot" while monitoring the mV output. However, this task is cumbersome and involves special equipment not typically integrated into rebreather designs; and even when the test is performed, the efficacy of the test is limited due to the fact that the conditions in the test pot (e.g. temperature, humidity) do not match those under which the sensor is used operationally (Sieber 2014). Some divers attempt to perform this test within the rebreather during the dive by manually flushing the rebreather loop with 100% oxygen at a depth of 66 ft (20 m) prior to descent. While this allows the test to be performed with appropriate operational temperature and humidity conditions, it is also cumbersome, requires some time to perform, wastes oxygen supplies, and is inaccurate due to difficulties in achieving a complete flush of the breathing loop. It also creates problems of "PO_2 spiking" when descent is resumed, especially if the rate of descent is fast. The incorporation of an ASV system, however, allows a variant of validation, called the "Hyperoxic Linearity Test" (HLT) to be performed automatically, quickly, and reliably. As the diver initially descends past 66 fsw (20 m), a variation of the ASV is performed using oxygen as the validation gas, thereby ensuring that the oxygen sensor is linear up to at least 1.6 bar. If this test fails, the oxygen setpoint used by the control system can be automatically reduced to 1.0 bar (where sensor linearity was confirmed during calibration).

As Jones (2014) has demonstrated, and as supported by a growing body of empirical data, a single sensor subjected to both PSV and ASV is superior in terms of reliability than three separate oxygen sensors using conventional voting logic. Indeed, one of the consensus statements from the Rebreather Forum 3 (Design and Testing 4) reads: "The forum strongly endorses industry initiatives to improve oxygen measurement technologies and advocates consideration of potentially beneficial emerging strategies such as dynamic [=active] validation of cell readings and alternatives to galvanic fuel cells." (Mitchell 2014b). With the accumulation of yet more data from divers in more circumstances (see section on "Data" below), the algorithms behind both PSV and ASV systems will only continue to improve and, perhaps, the number of rebreather diving fatalities can be reduced.

Carbon dioxide monitoring

The second leading cause of fatalities among rebreather divers is hypercapnia (elevated CO_2) (Fock 2014). Absorbent material that is spent, wet, inadequately packed, or used in poorly-designed or incorrectly-assembled canisters, or otherwise used outside the operational range can fail to absorb CO_2 at the rate it is produced by a rebreather diver. This leads to an increase in inspired CO_2 and consequently increased levels of CO_2 in the blood, which can cause a wide range of symptoms, including increased susceptibility to CNS oxygen toxicity, disorientation, and loss of consciousness (among other less life-threatening symptoms) (Doolette and Mitchell 2011; Mitchell 2014a; Gurr 2014; Warkander 2014).

Although much attention has focused on ensuring safe levels of oxygen in rebreathers, until recently comparatively little effort has focused on monitoring CO_2 levels in rebreathers. Most rebreather designs have relied on either a simple time-based limit to canister duration based on empirical testing under conservative circumstances (e.g., cold water temperatures, high workload, and relatively deep water). Because most divers do not operate under such conditions, this approach can sometimes lead to excessively conservative limits to absorbent canister durations, which can lead divers to "guestimate" longer durations, sometimes leading to serious problems. A slightly more sophisticated approach is to base canister duration limits on metabolic oxygen consumption. Because the ratio of oxygen consumed to CO_2 produced by a diver is relatively stable for most people in most situations, this approach can compensate for variations in diver workload and base metabolism. However, it generally does not adequately compensate for the effects of depth and absorbent temperature on canister duration, and calculations of oxygen metabolically consumed by the diver can be inaccurate due to a variety of factors (Gurr 2014; Warkander 2014).

A more direct approach to monitoring CO_2 absorbent status (and, by inference, canister break-through) takes advantage of the exothermic nature of the reaction of absorbent material binding with CO_2 molecules. In most axial-flow canister designs, there is a relatively compressed "front" of active CO_2 absorption, and this "front" can be detected thermally. Absorbent material that has already been largely consumed will be less active in binding CO_2, and therefore lower in temperature due to reduced exothermic reactions. Several rebreather manufacturers (e.g., AP Valves, VR Technologies, Hollis) have developed arrays of temperature sensors within the absorbent material that can be used to detect the position of the active "front" within the absorbent bed (Figure 2). The advantage of this approach is that the performance of the absorbent bed as a whole can be monitored, effectively enabling the system to serve as a "fuel gauge" for predicting remaining canister life (Warkander 2014). However, both time-prediction approaches (with and without incorporation of metabolic oxygen consumption) and temperature sensor arrays have limited or no ability to detect canister bypass, channeling, or badly packed or spent absorbent material (Gurr 2014). To effectively address these issues, a more direct monitoring of inspired CO_2 through the use of a sensor is necessary.

Figure 2. Example temperature sensor array for monitoring CO_2 absorbent canister function, from AP Diving.

In the early 1990s, Cis-Lunar Development Laboratories worked with Teledyne Analytical Instruments to develop a functional CO_2 sensor for use on the MK-III rebreather. The sensor was extremely accurate in testing conditions, but was susceptible to inaccurate readings in environments subject to high humidity and condensation (as are typically found within a rebreather breathing loop). Subsequent efforts to develop functional real-time CO_2 sensors for rebreathers general met with limited success. The main limitations of most CO_2 sensing technology of the time involved issues operating in high humidity and depth compensation. In 2009, VR Technologies released the first commercial CO_2 sensor for rebreathers (Gurr 2014). The issue with humidity is reduced through the use of special hydrophobic materials that help prevent humidity from reaching the sensor, without restricting gas flow to the sensor too much. Several other manufacturers have released commercial CO_2 sensors for rebreathers (Figure 3), but they have yet to gain widespread adoption. This is, in part, due to their relatively high cost, tendency towards inaccurate readings in some situations, and the fact that they are really only effective at detecting failures, rather than predicting remaining canister duration (Warkander 2014).

Figure 3. Example CO_2 sensors from VR Technologies (left), Hollis (center) and AP Diving (right).

Monitoring remaining canister life and detecting the CO_2 concentration of the inspired gas address some, but not all of the problems associated with CO_2 in rebreathers. In the case of CO_2 sensors, exact placement of the sensor within the breathing loop is important. Ideally, the gas would be sensed directly within the mouthpiece, as this represents the gas actually being inhaled by the diver (e.g., dead-space within the mouthpiece itself, and failure of the exhalation check-valve of the mouthpiece can contribute to elevated inspired CO_2 levels that would not be detected by placing the sensor further upstream in the breathing pathway). Moreover, hypercapnia is defined in terms of increased levels of CO_2 in the diver's blood, and inspired CO_2 is only one contributing cause. Other causes of hypercapnia in rebreathers include work of breathing, diver fitness, respiratory ventilation patterns and behavior, and other mechanical and physiological factors (Mitchell 2014a; Gurr 2014; Warkander 2014). The ideal solution is to monitor CO_2 levels in both the inhalation and exhalation of the diver, in combination with temperature sensor arrays in the canister to more accurately predict remaining canister duration. To achieve this, small, fast, and relatively inexpensive CO_2 sensors that function reliably even in wet and humid conditions will be necessary.

Automated pre-dive checklist

The importance of using pre-dive checklists for rebreather diving operations has been strongly and universally endorsed (Bozanic 2002; Tetlow and Jenkins 2005; Richardson and Vann 2014; Menduno 2014; McDonald and Lang 2014; Short 2014; Partridge 2014; Heinerth 2014; Whatley 2014; Kohler 2014; and many others). The first section of the Rebreather Forum 3 Consensus statement is entirely devoted to checklists, and reads as follows (Mitchell 2014b):

> *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 pre-dive preparation (unit assembly and immediate pre-dive) and post-dive 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 become second nature.*

Despite this broad advocacy, checklists are not consistently implemented among different rebreather models, or by individual rebreather divers. Recognizing the fallibility of human discipline in maintaining a regimented approach to a manual (paper-based) checklist, Cis-Lunar Development Laboratories included an electronic pre-dive checklist in their MK-5P rebreather (Pyle 1997). Based on the success of this feature, the automatic electronic pre-dive checklist was significantly expanded and enhanced in subsequent generations of rebreather designs in the Poseidon MK-VI and SE7EN rebreathers. It now includes a robust series of internal diagnostics for all core electronic components (microprocessors, memory, firmware versions, decompression data, solenoid valves, depth sensor, oxygen sensors, mouthpiece position sensors, alarm lights, displays, network integrity, power consumption, gas pressures, and many other factors), in addition to automatic oxygen sensor calibration, automatic positive pressure loop test, prompts for confirmation of gas concentrations and CO_2 absorbent canister installation, open-circuit regulator functionality, and a five-minute timer for system pre-breathe (Stone and Pyle 2009; Poseidon Diving Systems 2014). Failure to complete the full pre-dive checklist results in a "Do Not Dive" state, in which attempts to conduct a dive will result in a suite of alarms.

There are several advantages of an automated, electronic checklist compared to traditional paper-based checklists Stone (2014). Perhaps the most significant advantage is that the system cannot be dived (at least not without a suite of warnings) if the pre-dive checklist has not been completed; thereby alleviating reliance on the discipline of individual divers to diligently perform a complete system checklist manually. Another advantage is that each step of the checklist, including full details of any measured parameters associated with each step of the checklist, are automatically logged. This information has proven to be invaluable for incident analysis. Another advantage is that the completion of the pre-dive checklist requires significantly less time. A full automatic electronic pre-dive checklist requires only about 3-4 minutes; whereas manual checklists can take much longer. Moreover, no paper or writing instruments are necessary to complete the process. Often in diving environments (e.g., open boats), it may be cumbersome for divers to complete manual checklists, increasing the temptation to bypass them entirely. Finally, incorporating the pre-dive checklist into the rebreather control system itself helps to establish a standard routine prior to the start of each dive, thereby increasing compliance and, ultimately, reducing risk.

Head-up displays

While the importance and complexity of monitoring and controlling gas mixtures in a rebreather loop cannot be over-stated, another aspect of rebreather design that is perhaps equally important and complex, but far less appreciated, is the way in which information is exchanged between the rebreather and the diver (referred to as the "human-machine interface," or HMI). In his analysis of rebreather fatalities, Fock (2014) wrote: "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." He went on to conclude: "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."

The HMI of rebreathers is generally comprised of two main components: alarm systems, and displays. These overlap in the form of alarms that are detected visually. The primary challenge of designing effective alarm systems for rebreathers is to strike the right balance between alerting the diver to a potential problem, but without habituating divers to alarms that are triggered too frequently. While it is important to ensure that divers are made aware of actual or potential problems with the rebreather operation, experience has shown that overly aggressive use of alarms – especially for situations that do not have an immediate bearing on the well-being of the diver and/or represent false alarms – can effectively train divers to ignore alarms entirely, and thereby miss alarms when they are triggered for truly important reasons. One solution to alarms that has proven successful has been to use a variety of alarm types that target different senses, including visual, auditory and tactile. An example of the latter that has proven particularly effective is the "display integrated vibrating alarm" (DIVA) developed by Juergensen Marine, Inc., which includes a vibrator alarm attached to the rebreather mouthpiece. The primary challenge of designing effective displays for rebreathers is to ensure that divers can (and will) regularly get access to the information they need about the operation of the rebreather and other factors (such as decompression information), when they need it. If too much information is presented on the display, divers may be confused or struggle to locate the correct information in a stressful situation. On the other hand, divers also need access to more detailed information, so either multiple displays, or multiple views on a single display, are sometimes necessary.

There are many aspects of designing displays for rebreathers to optimize the HMI, balancing the needs of alarms, general information, human factors, and redundancy, most of which are beyond the scope of this discussion. However, one recent trend in rebreather displays that will likely continue to advance involves a new generation of head-up display (HUD) devices. HUDs have been used in the aviation industry (particularly in military aircraft) for years. The basic idea of HUDs in general is to provide information to a user that does not require hands or any action (other than glancing to a certain part of the field of vision) to access. Many rebreathers incorporate some form of HUD, usually involving one or more colored LEDs to convey alarms or other information to the diver (Figure 4). These have ranged from a single LED to alert a diver of a generic potential problem (e.g., the Carleton Technologies MK-16), to an array of colored LEDs for various alarms and other information (Cis-Lunar MK-IV and MK-5P, AP Diving Vision, VR Technologies Sentinel, InnerSpace Systems, and many others), to more complex systems that include vibrator alarms (e.g., Juergensen Marine Inc. DIVA and Poseidon MK-VI Discover and SE7EN (Figure 5).

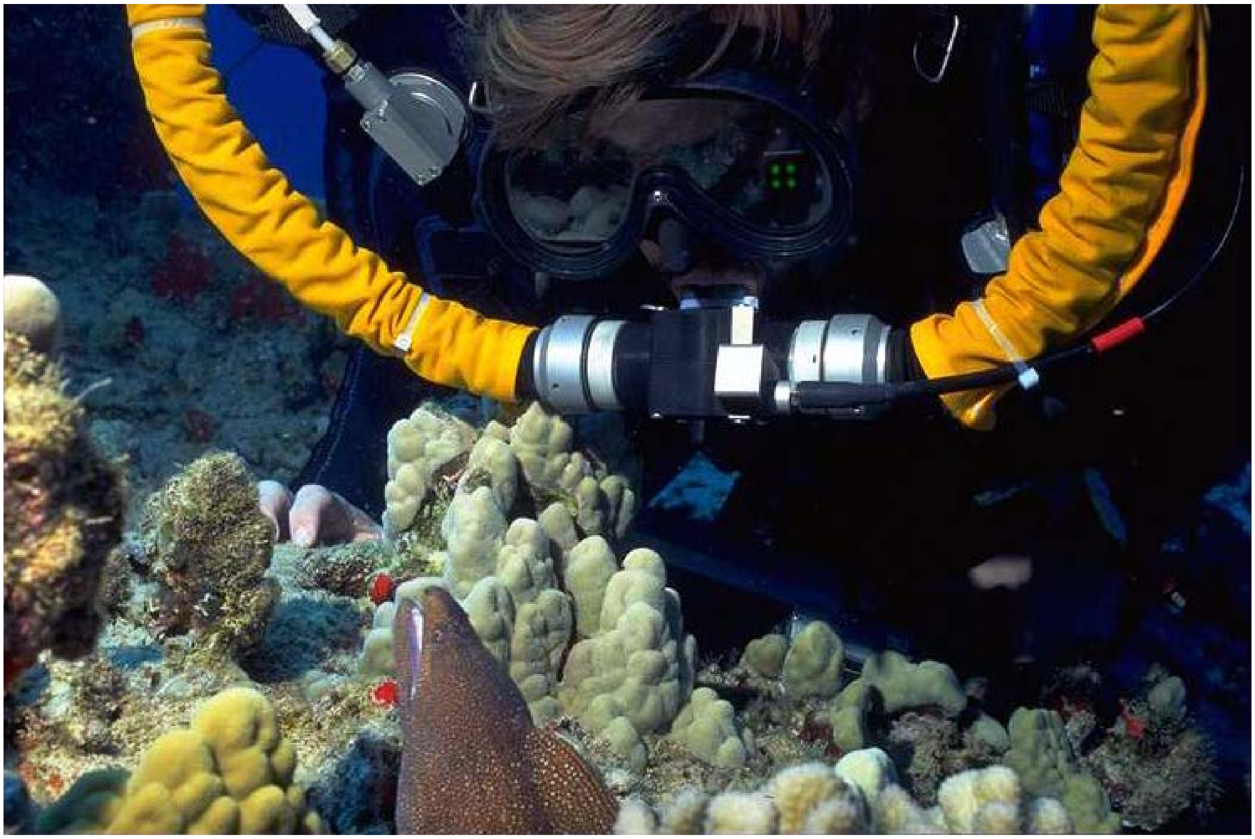


Figure 4. The author using a Cis-Lunar MK-IV rebreather, equipped with a four-LED HUD (as seen in the reflection in the mask). Photo: Mark Mader.

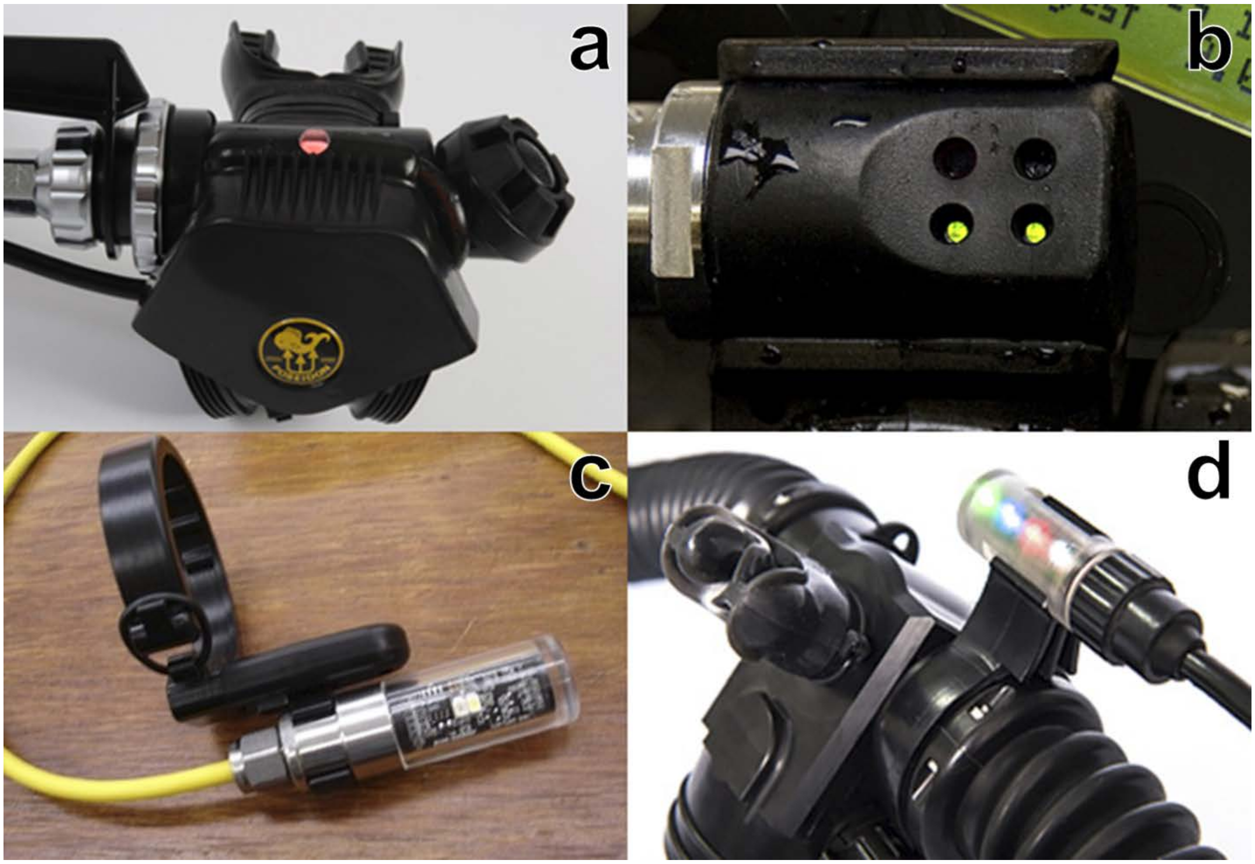


Figure 5. Example LED-based HUDs from Poseidon Diving Systems (a), AP Diving (b), Juergensen Marine Inc. (c) and VR Technologies (d).

Although LED-based HUDs can be valuable for getting the diver's attention and conveying basic information, they are limited in terms of their capabilities for HMI functions of a rebreather. While some systems do provide information to divers about current PO_2 levels through different colors of lights and certain blinking patterns, the amount of information that can be communicated through one or a few LEDs is very limited. Moreover, divers can sometimes tune out simple lights in their field of view, potentially defeating the effectiveness of alarms. A more effective HUD would convey more complex information to the diver via a virtual image within the diver's field of view, analogous to certain military aircraft.

One of the earliest examples of an information-rich HUD for divers is the DataMask HUD from Oceanic (Oceanic 2002), which includes a built-in dive computer with a display embedded within the mask itself. Similar devices have been developed specifically for rebreathers by the military (Gallagher 1999; Belcher et al. 2003). More recently, several manufacturers have produced information-rich HUDs specifically for rebreathers (Figure 6). The first of these was initially developed by Dive Systems and Poseidon Diving Systems, and later produced by SEABEAR Diving Technology and also available as the AP Diving Head-Up Screen (HUS) (Sieber et al. 2009; Koss and Sieber 2011a; Koss and Sieber 2011b; Sieber et al 2013). A similar device, the Near Eye Remote Display (NERD) was developed and is produced by Shearwater Research (Shearwater Research 2014).

Figure 6. Example information-rich HUDs, including Diving Systems HUD (a), Shearwater Research NERD (b), SEABEAR Diving Technology (c), and AP Diving HUS (d).

These information-rich HUDs represent an important step forward in HMI options for rebreathers. Their primary advantage over LED-based HUDs is that they can convey detailed information (Alarms, PO_2, decompression information, compass and other navigation information, etc.) and also attention-grabbing alarms in a way that is less confusing and more useful than what can be communicated through different colors and blinking patterns of LEDs. As they become smaller, more reliable, and less expensive, these devices will increasingly become standard equipment on rebreathers, and this should reduce the rate of rebreather diving fatalities. As they become more powerful and incorporate higher-resolution displays, they will become especially valuable to diving scientists, with the ability to stream video and scientific data in addition to rebreather system data.

Next Steps

It is always difficult to predict the future of technological development for any field. However, there are certain trends in new rebreather technology that are actively under development, in many cases by more than one manufacturer, that are showing promising signs of economic viability within the next few years. These include the incorporation of gas sensors that do not rely on standard galvanic reactions, various alternatives for closed-circuit bailout systems, real-time logging of ever-increasing amounts of high-resolution data during dives, analysis of these data with powerful microprocessors for real-time electronic control system integrity, and (ultimately) sophisticated semi-autonomous underwater robots to improve diver safety. This certainly does not represent an exhaustive list of new rebreather technologies currently in development by various manufacturers, but these are areas of technology development that appear to be close to implementation (to varying degrees), and/or are being pursued by more than one manufacturer.

Non-galvanic sensors

As previously noted, one of the consensus statements from Rebreather Forum 3 (Design and Testing 4) strongly endorsed initiatives to consider "alternatives to galvanic fuel cells." (Mitchell 2014b). This recommendation emerged from a recognition of the inherent limitations and issues associated with the galvanic oxygen sensors used in most modern rebreathers. These limitations include temperature compensation, erroneous readings resulting from condensation, response time, longevity, current-limiting effects, and other factors (Sieber 2014). In addition to sensor validation techniques as described previously, the efficacy of galvanic oxygen sensors can be improved by incorporating additional electronics (including an analog-to-digital converter) into the sensor itself, converting it into a "smart galvanic sensor" (Sieber 2014). Although this concept has been investigated in several projects, it has not yet gained widespread implementation, and is limited in that it represents only an incremental improvement over standard analog galvanic oxygen sensors.

A more promising approach is the ongoing development of alternatives to galvanic oxygen sensors. These alternatives include optical oxygen sensors (which measure the fluorescence of a specially treated material) (Borisov et al. 2008; Fischer et al. 2010; Sieber 2014) and solid-state oxygen sensors (Dubbe 2003; Bhoga and Singh 2007; Park et al. 2009; Sieber et al. 2011; Sieber 2014).

Closed-circuit bailout

One of the most significant logistical challenges for deep diving with rebreathers is the management of open-circuit bailout supplies (Pyle 1996a, Harris 2014). Although rebreathers themselves provide dramatically extended life-support times for a given mass of equipment, the necessity to allow for a safe return to the surface in the event of a catastrophic rebreather failure usually requires multiple large-capacity cylinders to be either carried by the diver, or positioned where they can be reliably accessed if needed. A much more efficient approach is to develop a closed-circuit bailout system, reducing the need for multiple large-capacity cylinders for open-circuit bailout.

Cis-Lunar Development Laboratories pioneered the concept of dual-loop rebreathers, starting with the "MK-I" (aka, "FRED") (Stone 1989; 1990). Dual-loop rebreathers have been built for all seven generations of Cis-Lunar/Poseidon rebreathers (Figure 7). Multiple-loop rebreather systems and separate bailout rebreathers have been built and used by others as well (e.g., Isler 1990; 1992; 1993; Starnawski

2011; Harris 2014). However, most of these have been in the form of prototypes or custom-built systems; they have not yet achieved widespread commercial availability. There are several key design challenges that must be overcome in order to develop a viable dual-loop or bailout rebreather. Perhaps foremost among them is the need to maintain proper gas volume and composition in the breathing loop not currently in use by the diver. The gas volume must be maintained in a way that compensates for depth changes without adversely impacting buoyancy control, and the gas composition must be continuously monitored and maintained as life-sustaining to ensure that a switch to a secondary loop is safe. The physical bulk of the entire system must not be too great, and the secondary mouthpiece must be stored in a location where it is both unobtrusive and easily accessible. Also, the primary advantage of dual-loop and bailout rebreathers is for deep decompression dives and long penetration cave dives. As such, whatever system is being used to calculate decompression must be able to accommodate a switch in breathing loop (with a commensurate switch in electronic control systems), while maintaining the ability to monitor real-time decompression. If this is done in a way that incorporates the measured inspired oxygen levels determined by the rebreather, there needs to be a mechanism for transferring decompression data from one system to the other, without compromising the independence of the two systems. Perhaps most importantly, the operational complexity and task-loading associated with managing two separate breathing loops must not be excessive, lest it be vulnerable to what many regard as the most unreliable aspect of any rebreather dive - the diver.

Figure 7. Prototype dual-loop rebreather system designed and tested by the author.

All of these limitations can be overcome, however; and the potential advantages for bailout rebreather systems are substantial enough (especially for expeditionary diving), that the solutions to the problems are worth investigating. As rebreather designs get smaller and electronic control systems become more sophisticated, the feasibility of designing practical closed-circuit bailout rebreathers increases.

Data

The aviation industry has long recognized the value of complete and accurate data logged during flights, in the form of so-called "black-box" data. Pyle (2014) summarized the importance of logging data from rebreather dives, particularly with regard to the utility of such data for accurate accident analysis, rebreather design testing and enhancement, and personal diver education. When aggregated, these data can provide extremely valuable insights on diving patterns across an entire population of divers, illuminating the elusive "denominator" in determining overall accident risk assessments.

As electronic rebreather control systems continue to increase in processing and storage capacity, the potential for capturing data at ever-increasing granularity expands. Parker (2014) wrote, "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." In 1994, the Cis-Lunar Mk-IV included a data logging system that recorded several hundred data points (or "events") per hour of dive time. By 1997, the Cis-Lunar Mk-5P logged more than a thousand events per hour of dive time. Ten years later, the next iteration of this line of rebreathers, the Poseidon MK-VI Discovery, captured between 15,000 and 25,000 events per hour; and today, the Poseidon SE7EN records more than twice this amount of data. The value of these data – for individual divers, for manufacturers, and for the rebreather community at large – cannot be overstated. One of the consensus statements from Rebreather Forum 3 (Design and Testing 1) reads: "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" (Mitchell 2014b). This recommendation is expanded and echoed by Parker (2014), Partridge (2014), Stone (2014) and Pyle (2014).

Pyle (2014) advocated the development of a centralized repository for dive-log data, both in terms of dives being conducted, and the data logged by rebreathers during the course of actual dives. Some data logged by rebreathers are very specific to individual models, and may involve data resulting from proprietary algorithms and logic. Thus, not all of the downloaded data will (or should) be willingly shared. However, certain core data values (such as time, depth, PO_2, water temperature, and alarm states) should minimally be shared, and optimally additional data on parameters, such as metabolic oxygen consumption rates, CO_2 levels and canister states, breathing loop temperature, respiratory rates, oxygen sensor confidence levels, and other information that could be valuable for characterizing populations of rebreather diver and their diving practices, should be shared as well.

Two examples of this sort of data aggregation in diving represent models for moving forward with rebreather data. The first is the "Project Dive Exploration" (PDE) program – a program in which Divers Alert Network (DAN) captured downloaded dive logs from nearly 200,000 open-circuit scuba dives to use for a variety of purposes, including accident analysis (Pollock et al. 2008). The second is the AAUS database for scientific divers (e.g., Sellers 2016). Although PDE is no longer active, the AAUS database continues to be maintained indefinitely. As the use of closed circuit rebreathers by diving scientists continues to increase, the AAUS should expand the existing data aggregation system to include additional details from individual dives – including core data from download rebreather dive log files – as part of its data management and aggregation service. Scientific divers represent the perfect community to develop data standards (modelled after the PDE standard) for more detailed dive data aggregation, which in turn can serve as a model for aggregating data on rebreather dives from the broader recreational rebreather diving community.

Real-time system analysis

The value of high-resolution data from rebreather dives is not limited to downloaded log files. As the microprocessors incorporated within rebreather control systems become more powerful, the ability to perform increasingly complex analysis of data generated during rebreather dives expands. Basic oxygen control systems, including voting logic, do not require sophisticated computations to manage. The first processor-intensive computations that rebreather electronics incorporated was real-time decompression, starting with the Cis-Lunar MK-I in the 1980s (Stone 1989; 1990). The state of available microprocessors in rebreathers at the time was such that decompression calculations needed to be distributed across multiple separate processors for parallel computations, in order to provide decompression information (such as the decompression ceiling and total time to surface) to the diver in (near) real-time. The microprocessors used by rebreathers today are orders of magnitude more powerful, and can easily perform calculations based on multiple different decompression models simultaneously, with plenty of processor cycles to spare.

The increased processing power of modern rebreather control systems opens new doors to a wide variety of real-time computational analysis that can only improve rebreather reliability. Throughout much of the recent history of rebreather diving, it has generally been accepted that a well-trained rebreather diver is better at interpreting oxygen sensor readings and other data than any computer algorithm could be. This is especially true for conventional voting logic, as alluded to earlier. However, increasingly, rebreather control system algorithms are becoming superior to even well-trained rebreather divers. For example, during more than a decade of diving with the Cis-Lunar MK-5P rebreather, there were about a dozen cases in which the computer's interpretation of the PO_2 in the breathing loop (based on voting logic) disagreed with my own interpretation during the dive. In each case, subsequent examination of the downloaded dive log data confirmed that my interpretation was correct. Since I began using the Poseidon MK-VI and SE7EN rebreathers (both of which incorporate passive and active sensor validation), there have been a few cases where the computer and I disagreed about the PO_2. In all of these cases, the computer was right and I was wrong.

There is an understandable psychological resistance to the notion that computer algorithms can be superior to human insight and intuition, especially in matters concerning decisions critical for life-support. However, as technology continues to improve at an accelerating pace, computer control systems are proving themselves to be superior to human brains in making critical decisions in real-time; whether in chess matches, braking systems in automobiles, auto-pilot systems in aircraft, or rebreather control systems. Within the next few years, as we accumulate an increasing amount of data on actual rebreather dive profiles and circumstances, computer-based algorithms will continue to improve, and the norm in rebreather operations will shift more towards "dive-by-wire" modes of operation (Stone 2014). What began as simple logic to decide when to inject oxygen into a breathing loop, has broadened to include more effective automated pre-dive diagnostics and testing to ensure proper rebreather function prior to the start of the dive, and has further matured into real-time sensor validation systems and algorithms to predict remaining canister life based on temperature readings in the absorbent material. This trend in real-time data analysis will continue to advance, leading to more reliable rebreather control systems and, ultimately, fewer diving accidents.

Robotics

Rebreathers are not the only form of underwater technology that is increasing in sophistication. Autonomous underwater vehicles (AUVs) are also becoming more sophisticated, with emphasis on positioning and navigation, water sampling, imagery, and mapping. Several aspects of AUVs make them more effective for underwater exploration and scientific research than divers, particularly in terms of greater depth and duration. They also have advantages in terms of cost and logistics compared to deep-sea submersibles and tethered remotely operated vehicles (ROVs). On the other hand, in situ divers can perform tasks that are difficult or impossible for these other underwater exploration technologies, particularly for documenting complex habitats such as caves and coral-reefs, and performing complex tasks such as collecting motile specimens.

During a five-year project funded by NOAA to explore deep coral reefs in the Hawaiian Islands, a team of divers conducted several operations that involved rebreather divers coordinating with submersibles to perform research in ways that would have been difficult or impossible for either technology to have completed individually (Pyle et al. 2015; Figure 8). In general, the submersible was used to survey large areas of habitat and identify sites of interest for divers, as well as carry bulky equipment; and the divers could descend along marker lines deployed by the submersibles at target sites and perform complex tasks that would have been difficult or impossible to perform by the submersible. A similar project involving submersibles and rebreather divers was conducted in Cocos Island in 2011 (Pyle 2011; Hall 2011).

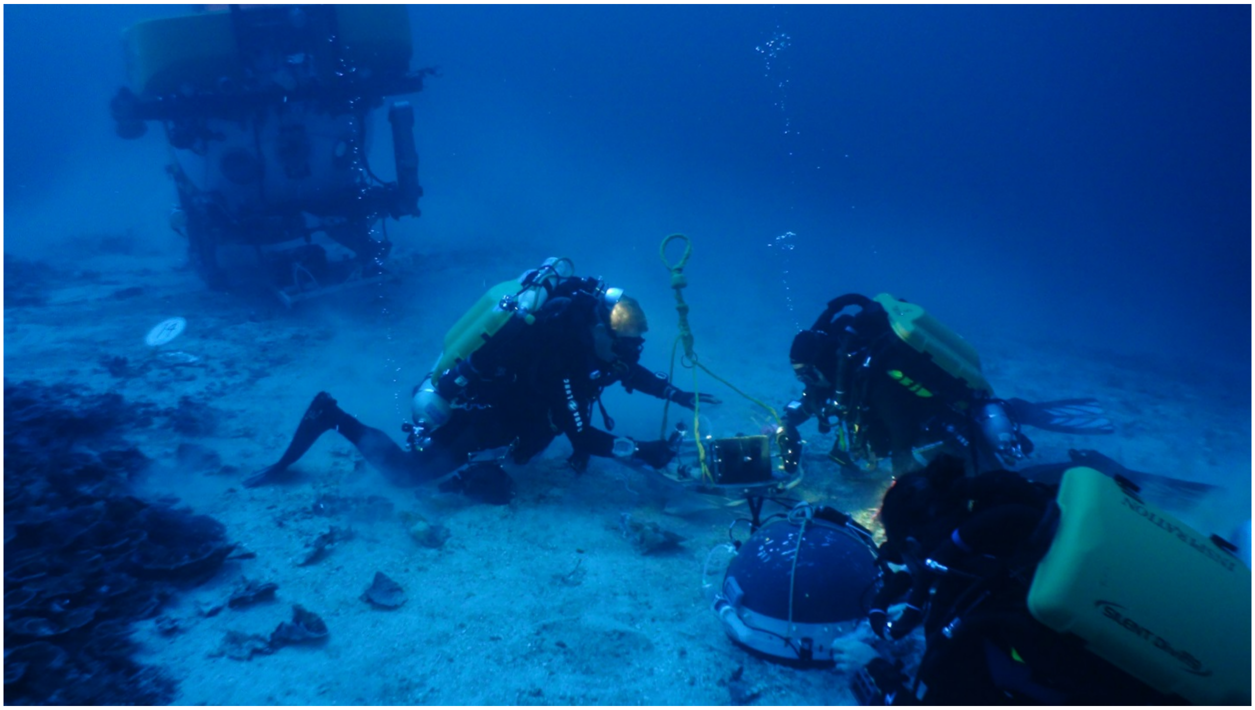


Figure 8. A team of rebreather divers conducts research on coral growth at a depth of 300 ft (90 m) off Maui, HI, in coordination with the University of Hawai'i's research submersible *Pisces V*. Photo by Richard L. Pyle.

Extending the concept of submersibles and rebreather divers working together, a team of engineers and underwater researchers have plans to develop an AUV system that is optimized to work together with rebreather divers to dramatically improve research opportunities in at least three distinct underwater environments (caves, under ice, and deep coral reefs). The AUV system, referred to as the "Generalized Underwater Autonomous Robot for Diver-Integrated Assistance and Navigation" (GUARDIAN), will combine technology developed for the "DEPTHx" and "VALKYRIE" AUVs (Gary et al. 2008; Stone et al. 2014) with the most advanced rebreather control systems to enable the AUV to function as a dive-team assistant and coordinator. Though in the early stages of development GUARDIAN represents an important technological advancement for improving effectiveness and safety of research divers.

Conclusions

As with any technology, the pace of rebreather technological capabilities development is accelerative. Several key advancements are already found in existing commercially available rebreathers. Real-time oxygen sensor validation during the dive represents a significant improvement over traditional three-sensor "voting logic," a new breed of improved CO_2 sensors designed for rebreathers can detect life-critical failures in CO_2 absorbent canister bypass or failure, and arrays of temperature sensors can serve as a "fuel gauge" for remaining canister life; automated pre-dive checklists offer key advantages over traditional paper-based manual checklists; and improved information access through more advanced head-up display systems will increase diver awareness of important parameter values and other rebreather system states. Other technologies are currently under development, and will likely appear in commercially available rebreathers in the coming years. New oxygen sensing technologies offer significant advantages of speed and reliability compared to existing galvanic fuel cells. Options for closed-circuit bailout will offer important logistical advantages for dives involving substantial decompression, or diving in physical overhead environments. More robust logging and aggregation of dive data, and better use of those data for system analysis in real time, will improve overall rebreather performance and safety. Advancements in AUV technology in combination with rebreather divers will improve both safety and operational efficiency and effectiveness. The scientific diving community stands to benefit from these technological advancements as much, if not more, than most other sectors of the diving industry. As such, scientific divers should play a more proactive role in promoting both the development of these technologies, and the adoption of them by more manufacturers. In some areas (data aggregation in particular), the scientific diving community is well-positioned to play a leadership role, not just in advancing the state of the art for scientific divers, but for the diving community at large.

Acknowledgments

I am particularly grateful to William C. Stone, Nigel A. Jones, Jonas Brandt, Thomas Oskarsson, and Arne Sieber for sharing their insights on the future development of rebreather technology.

References

Belcher EO, Gallagher DG, Barone JR, Honaker RE. Acoustic lens camera and underwater display combine to provide efficient and effective hull and berth inspections. In: Proceedings of Oceans 2003, San Diego, CA. 2003: 1361-7.

Bhoga SS, Singh K. Electrochemical solid-state gas sensors: an overview. Ionics. 2007; 13: 417-27.

Borisov S, Nuss G, Klimant I. Red light-excitable oxygen sensing materials based on platinum(II) and palladium(II) benzoporphyrins. Anal Chem. 2008; 80(24 suppl): 9435-42.

Bozanic JE. Understanding Rebreathers, 1st ed. Best Publishing: Flagstaff, AZ, 2002.

Collette BB. Results of the Tektite Program: Ecology of Coral-Reef Fishes. In: Lang MA, Baldwin CC, eds. Methods and Techniques of Underwater Research. Proceedings of the American Academy of Underwater Sciences Scientific Diving Symposium. Washington, DC: Smithsonian Institution; 1996: 83-7.

Collette B, Earle SA (eds). Results of the Tektite Project: ecology of coral reef fishes. Sci Bull Nat Hist Mus LA County. 1972; 14: 1-180.

Davis RH. Deep Diving and Submarine Operations (6th ed.). Tolworth, Surbiton, Surrey: Siebe Gorman & Company Ltd.; 1955; 693 pp.

Doolette DJ, Mitchell SJ. Hyperbaric conditions. Compr Physiol. 2011; 1(1): 163-201.

Dubbe A. Fundamentals of solid-state ionic micro gas transducers. Transducer Actuators B. 2003; 88: 128-48.

Fischer LH, Borisov SM, Schaeferling M, Klimant I, Wolfbeis OS. Dual sensing of PO_2 and temperature using a water-based and sprayable fluorescent paint. Analyst. 2010; 135(6): 1224-9.

Fock A. Analysis of recreational closed-circuit rebreather deaths 1998–2010. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 119-27.

Gallagher DG. Development of miniature, headmounted, virtual image displays for navy divers. In: Oceans '99 MTS/IEEE: Riding the Crest into the 21st Century; 1999; (3): 1098-104.

Gary M, Fairfield N, Stone WC, Wettergreen D, Kantor G, Sharp JM Jr. 3D mapping and characterization of sistema Zacatón from DEPTHX (DEep Phreatic THermal eXplorer). In: Yuhr LB, Alexander EC Jr, Beck BF. Proceedings of KARST08: 11th Sinkhole Conference. ASCE. 2008: 202-12.

Gurr K. CO_2 monitoring and canister limits in rebreathers. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 203-7.

Hall H. The sound of silence. Ocean Realm. 1990; Fall: 12-3.

Hall H. DeepSee Synergy. Howard Hall Productions. 2011 [accessed 22 May 2015]. http: //vimeo.com/47595340

Hamilton RW. Technology inspired: The closed-circuit rebreather. aquaCorps. 1990; 2: 10-4.

Hanlon RT, Hixon RF, Hendrix JP Jr., Forsythe JW, Sutton TE, Cross MR, Dawson R, Booth L. The application of closed circuit scuba for biological observations. In: Blanchard J, Mair J, Morrison, I, eds. Proceedings of the Sixth International Scientific Symposium of CMAS, Proceedings of the Diving Science Symposium. London: National Environmental Research Council; 1982: 43-52.

Harris R. Rebreathers: overcoming obstacles in exploration. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 56-61.

Heinerth JE. Five golden rules: shifting the culture of rebreather diving to reduce accidents. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014:241-5.

Isler O, Le RI. 2000: un precurseur de la plongee souterraine du future. UIS Cave Diving Magazine (Gorizia, Italy); 1990.

Isler O. Emergence du Ressel. UIS Cave Diving Magazine (Gorizia, Italy); 1992.

Isler O. Measured elegance. aquaCORPS. 1993; N7: 7-10.

Jones NA. PO_2 sensor redundancy. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 193-202.

Kohler R. Failure is not an option: the importance of using a CCR checklist. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 246-51.

Koss B, Sieber A. Development of a graphical head-up display (HUD) for rebreather diving. Int J Soc Underwater Tech. 2011a; 29(4): 203-8.

Koss B, Sieber A. Head-mounted display for diving computer platform. Journal of Display Technology. 2011b; 7(4): 193-9.

Kushman L. Cryogenic rebreather. Skin Diver. June 1969.

Lindfield SJ, Harvey ES, McIlwain JL, Halford AR. Silent fish surveys: bubble-free diving highlights inaccuracies associated with SCUBA-based surveys in heavily fished areas. Methods Ecol Evol. 2014; 5(10): 1061-9.

Lobel PS. Fish bioacoustics and behavior: passive acoustic detection and the application of a closed-circuit rebreather for field study. Mar Tech Soc J. 2001; 35: 19-28.

Lobel PS. Scuba bubble noise and fish behavior: a rationale for silent diving technology. In: Godfrey JM, Shumway SE, eds. Proceedings of the American Academy of Underwater Sciences 24th Annual Symposium Groton, CN: University of Connecticut; 2005: 49-59.

McDonald CM, Lang MA. Rebreather perspective: The scientific-diving community. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 35-43.

Menduno M. In the loop: the report from aquaCORPS' Rebreather Forum. aquaCORPS. 1994; N8.

Menduno M. Building a consumer rebreather market: lessons from the technical diving revolution. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 2-23.

Mitchell SJ. Physiology of rebreather diving. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014a: 80-90

Mitchell SJ. Rebreather forum 3 consensus. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014b: 287-302.

Nordstrom R. Looking ahead: closed-circuit underwater breathing apparatus (CCUBA). In: Mount T, Gilliam B, eds. Mixed Gas Diving: The Ultimate Challenge for Technical Divers. San Diego, CA: Watersports Publishing, Inc.; 1993: 341-60.

Parker M. Quality assurance through real-time monitoring. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 137-47.

Partridge BG. Rebreather information systems. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 148-52.

Oceanic. Oceanic Datamask Operating Manual. http: //www.oceanicworldwide.com/us/media/wysiwyg/manuals/12-2736-r02.pdf. 2002; [last accessed 22-May-15]; 147 pp.

Palmer R, ed. Underwater Expeditions, 3rd Edition. London: Expedition Advisory Centre. 1990; 136 pp.

Parrish FA, Pyle RL. Field comparison of open-circuit scuba to closed-circuit rebreathers for deep mixed-gas diving operations. Mar Tech Soc J. 2002; 36(2): 13-22.

Park CO, Fergus JW, Miura N, Park J, Choi A. Solid-state electrochemical gas transducers. Ionics. 2009; 15: 261-84.

Parker M. Quality assurance through real-time monitoring. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 137-47.

Pence DF, Pyle RL. University of Hawaii dive team completes Fiji deep reef fish surveys using mixed-gas rebreathers. SLATE. 2002; April: 1-3.

Pollock NW, Dunford RG, Denoble PJ, Dovenbarger JA, Caruso JL. Report on decompression illness, diving fatalities and Project Dive Exploration: 2008 Edition (based on 2006 data). Durham, NC: Divers Alert Network. 2008; 137 pp.

Poseidon Diving Systems. Poseidon SE7EN user manual. Göteborg, Sweden: Poseidon Diving Systems AB. 2014; 97 pp.

Pyle RL. A learner's guide to closed-circuit rebreather diving. In: Richardson D, Menduno M, Shreeves K. Proceedings of Rebreather Forum 2.0. Diving Science and Technology Inc. 1996a: P45-P67.

Pyle RL. The Twilight Zone. Natural History. 1996b; 105(11): 59-62.

Pyle RL. MK-5P Electronically Controlled, Mixed-Gas Closed-Circuit Rebreather: Manual of Operation. Version 1.0. Cis-Lunar Development Laboratories. 1997; 136 p.

Pyle RL. Chapter 7. Use of advanced mixed-gas diving technology to explore the coral reef "Twilight Zone". In: Tanacredi JT, Loret, J. eds. Ocean Pulse: A Critical Diagnosis. New York: Plenum Press; 1998: 71-88.

Pyle RL. Mixed-gas, closed-circuit rebreather use for identification of new reef fish species from 200-500 fsw. In: Hamilton RW, Pence DF, Kesling DE, eds. Assessment and Feasibility of Technical Diving Operations for Scientific Exploration. Nahant, MA: American Academy of Underwater Sciences. 1999: 53-65.

Pyle RL. Assessing Undiscovered Fish Biodiversity on Deep Coral Reefs Using Advanced Self-Contained Diving Technology. Mar Tech Soc J. 2000; 34(4): 82-91.

Pyle RL. Submersibles, Camera, Action! New York Times Green Blog. 21 December 2011 [accessed 22 May 2015]. http: //green.blogs.nytimes.com/2011/12/21/cameras-submersibles-action/

Pyle RL. Toward a new era in recreational and technical rebreather diving. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 173-84.

Pyle RL, Boland R, Bolick H, Bowen BW, Bradley CJ, Kosaki RK, Langston R, Longenecker K, Montgomery AD, Parrish FA, Popp, BN, Rooney J, Smith CM, Wagner D, Spalding HL. A comprehensive investigation of mesophotic coral ecosystems in the Hawaiian Archipelago. PeerJ: in press.

Pyle RL, Lobel PS, Tomoleoni JA. The value of closed-circuit rebreathers for biological research. In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Wrigley Marine Science Center, Catalina Island, CA; 2016; 116-130.

Pyle RL, Stone WC, Jones N, Brandt, J. A New Approach to Closed-Circuit Rebreather Gas Monitoring: Why Two Oxygen Sensors can be Better than Three. Göteborg, Sweden: Poseidon Diving Systems AB. 2009: 14 p. doi: 10.5281/zenodo.17661.

Quick D. A History of Closed Circuit Oxygen Underwater Breathing Apparatus. Royal Australian Navy, School of Underwater Medicine; 1970, RANSUM-1-70.

Richardson D, Menduno M, Shreeves K. Proceedings of Rebreather Forum 2.0. Diving Science and Technology Inc. 1996.

Richardson D, Vann R. Forward. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 1.

Rowley SJ. Refugia in the 'twilight zone': discoveries from the Philippines. The Marine Biologist. 2014; 2: 16-7.

Sellers SH. Overview of rebreathers in scientific diving 1998-2013. In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Wrigley Marine Science Center, Catalina Island, CA; 2016; 5-39.

Shearwater Research. Shearwater NERD User Manual, Revision B. Vancouver, BC: Shearwater Research 2014; 80 pp.

Sherman C, Appeldoorn R, Carlo M, Nemeth M, Ruíz H, Bejarano I. Use of technical diving to study deep reef environments in Puerto Rico. In: Pollock NW, ed. Diving for Science 2009. Proceedings of the American Academy of Underwater Sciences 28th Symposium. Dauphin Island, AL: AAUS; 2009: 58-65.

Short P. Technical-diving community. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 51-2.

Sieber A. Oxygen sensor technology for rebreathers. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 185-92.

Sieber A, L'Abbate A, Bedini R. Oxygen sensor signal validation for the safety of the rebreather diver. Diving Hyperb Med. 2008; 38: 38-45.

Sieber A, Jones NA, Stone B, Pyle R, Koss B, Sjöblom K. Embedded Systems in the Poseidon MK6 Rebreather. Lecture Notes in Electrical Engineering. 2009; 81: 33-44.

Sieber A, Pyle R. A review of the use of closed-circuit rebreathers for scientific diving. International Journal of the Society for Underwater Technology. 2010; 29(2): 73-8. http: //dx.doi.org/10.3723/ut.29.073

Sieber A, Baumann R, Fasoulas S, Krozer A. Solid-state electrolyte sensors for rebreather applications: a preliminary investigation. Diving Hyperb Med. 2011; 41(2): 90-6.

Sieber A, Schuster A, Reif, S, Madden D, Enoksson P. Head-up display system for closed circuit rebreathers with antimagnetic wireless data transmission. Mar Tech Soc J. 2013; 47(6): 42-51.

Starnawski K. 222m on dual CCR. Advanced Diver Magazine Online. 2011 [accessed 22 May 2015]. http: //www.advanceddivermagazine.com/articles/dualccr/dualccr.html

Starck WA. Electrolung. aquaCORPS. 1993; N7: 6-8.

Starck WA III, Starck JD. From the Bahamas to Belize: Probing the deep reef's hidden realm. Nat Geogr. 1972; 149(12): 867-86.

Stone WC (ed.) The Wakulla Springs Project. Derwood, MD: U.S. Deep Caving Team; 1989; 213 pp.

Stone WC. Exploring underwater with a failsafe diving rebreather. Sea Tech. 1990; (12): 17-23.

Stone B. Rebreather hazard analysis and human factors, or how we can engineer rebreathers to be as safe as OC SCUBA. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 153-72.

Stone WC, Hogan B, Siegel V, Lelievre S, Flesher C. Progress towards an optically powered cryobot. Ann Glaciol. 2014; 55(65): 1-13. doi: 10.3189/2014AoG65A200.

Stone WC and Pyle RL. MkVI Discovery Electronically-Controlled Closed-Circuit Rebreather: User's Guide Version 2.0 (Firmware Version 42). Göteborg, Sweden: Poseidon Diving Systems AB. 2009: 93 p.

Tetlow S, Jenkins S. The use of fault tree analysis to visualize the importance of human factors for safe diving with closed-circuit rebreathers (CCR). Int J Soc Underwater Technol. 2005; 26(3): 105-13.

Tomoleoni JA, Weitzman BP, Young C, Harris M, Hatfield BE, Kenner M. Closed-circuit diving techniques for wild sea otter capture. In: Steller D, Lobel L, eds. Diving for Science 2012. Proceedings of the American Academy of Underwater Sciences 31st Symposium. Dauphin Island, AL: AAUS. 2012: 193-9.

Tricas TC, Boyle KS. Acoustic behaviors in Hawaiian coral reef fish communities. Mar Ecol Prog Ser. 2014; 511: 1-16.

Tzimoulis P. 300 feet on computerized scuba. Skin Diver. 1970; 19(9): 28-33.

Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014. 324 pp. http: //media.dan.org/RF3_web.pdf

Warkander DE. CO_2 scrubber technology: why, how and how long. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 208-15.

Whatley J. Rebreather education and safety association (RESA). In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 62-3.

QUESTIONS AND DISCUSSION

DAVE CONLIN: Does the algorithm differentiate between whether you are measuring higher or lower than expected values?

RICHARD PYLE: Yes. The reason why we are able to develop the algorithms to do these things is -- the art in that is not doing what I just showed you. The art is, one, coming up with the algorithm that predicts what the sensor will do under this set of conditions given all these multiple parameters. And, two, deciding whether you accept or reject the oxygen sensor's validity depending on how it deviates. And there are very different ways it can deviate. There are a lot of factors going into it. It is a complex answer to your question.

NEAL POLLOCK: The solid state sensor, which do you think is the closest to being ready?

RICHARD PYLE: It is going to be neck and neck between CO_2 and O_2. There are multiple different kinds of solid state sensors. It is kind of a misleading term. Basically what we are saying is non-galvanic, non-fuel cell. In a way, it is a little heartbreaking because that whole validation routine was all built around galvanic cells. So that whole oxygen sensor validation thing goes out the window. I would say solid state oxygen sensors are closer. I would be surprised if we do not start seeing them at DEMA this year, certainly DEMA next year. And the CO_2 sensors are already out there. The trick with them is making sure you have got the right calibration under different conditions.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

Respiratory Physiology of Rebreather Diving

Gavin Anthony[1], Simon J. Mitchell[2]*

[1] QinetiQ, Gosport, Hampshire, United Kingdom
[2] Department of Anaesthesiology, University of Auckland, Auckland, New Zealand
sj.mitchell@auckland.ac.nz
* corresponding author

Abstract

The use of rebreathers imposes a number of stresses on the respiratory system that frequently provoke retention of carbon dioxide (CO_2) during diving. The most important physiological mechanism leading to CO_2 retention is a derangement of the control of breathing which is usually responsible for subconsciously adjusting lung ventilation to keep the arterial CO_2 (P_aCO_2) at a normal level. When the work of breathing increases during diving there is a tendency for this breathing control system to become insensitive to rising P_aCO_2. An elevated P_aCO_2 can cause unpleasant and dangerous symptoms, increase inert gas narcosis, and predispose to cerebral oxygen toxicity. It follows that strategies to mitigate the risk of CO_2 retention in rebreather diving are important. These include minimising the work of breathing through appropriate rebreather design, taking account of respired gas density when planning rebreather dives, minimising physical exertion (particularly when deep), and meticulous attention to equipment preparation and adherence to best practice guidelines for replacement of CO_2 absorbent material.

Keywords: diving, rebreather, carbon dioxide, breathing, ventilation, hypercapnia

Introduction

The principal function of the lungs is to bring venous blood and gas in the lung alveoli into close proximity so that carbon dioxide (CO_2) in the blood may be exchanged for oxygen (O_2) in the alveoli. In healthy individuals the lungs are remarkably efficient at this task, and ventilation (the volume of gas moved in and out of the alveoli per unit time) is 'automatically' controlled (see below) to maintain adequate oxygenation (an arterial blood PO_2 [P_aO_2] between 80 and 100 mm Hg) and normal CO_2 levels ('normocapnia' – an arterial blood PCO_2 [P_aCO_2] around 38±7.5 mm Hg [2SD]).

During diving the inspired PO_2 is almost always elevated to planned and safe levels of 'hyperoxia'. Thus, in the absence of equipment malfunction or diver error, hypoxia or symptomatic hyperoxia are unexpected. In contrast, both immersion and the use of rebreathers (or other underwater breathing apparatus) impose challenges to maintenance of normal respiratory control and CO_2 homeostasis. As a result, a P_aCO_2 higher than normal (hypercapnia) is frequently encountered in the absence of any error or equipment related problem. This is important because hypercapnia can augment inert gas narcosis, increase the risk of oxygen toxicity, and produce unpleasant symptoms such as shortness of breath, confusion, anxiety, and ultimately unconsciousness.

This article will focus on the physiological mechanisms which may lead to hypercapnia during diving. It will begin with a brief account of normal CO_2 physiology. It will then examine the reasons why the work of breathing may increase when a diver is immersed using rebreathers, and the physiological basis for this to cause hypercapnia. Finally, it will examine the strategies divers may use to mitigate these physiological challenges. With the target scientific diver audience in mind, the article is deliberately written in a didactic style and does not assume detailed prior knowledge. It is not intended as a comprehensive academic work on the subject. Such treatments can be found elsewhere (Doolette and Mitchell 2011).

Normal CO_2 Physiology

Carbon dioxide is a by-product of metabolism of oxygen in cells. It is a volatile acid and will produce unwanted biochemical derangements (and symptoms as mentioned above) if levels in the body are allowed to increase. CO_2 diffuses from tissues to venous blood and is carried to the lungs where it diffuses from blood to alveoli and is breathed out. Maintenance of the diffusion gradient that drives this process is entirely dependent on movement of fresh gas in and out of the lungs ('ventilation'). Thus, greater ventilation will remove more CO_2 from the alveoli, thus maintaining an increased partial pressure gradient for CO_2 diffusion from the venous blood. Conversely, less ventilation will remove less CO_2 from the alveoli and less CO_2 will be removed from the blood. The crucial message here is that the amount of CO_2 eliminated from the body is directly proportional to ventilation. The relevant processes are depicted in Figure 1.

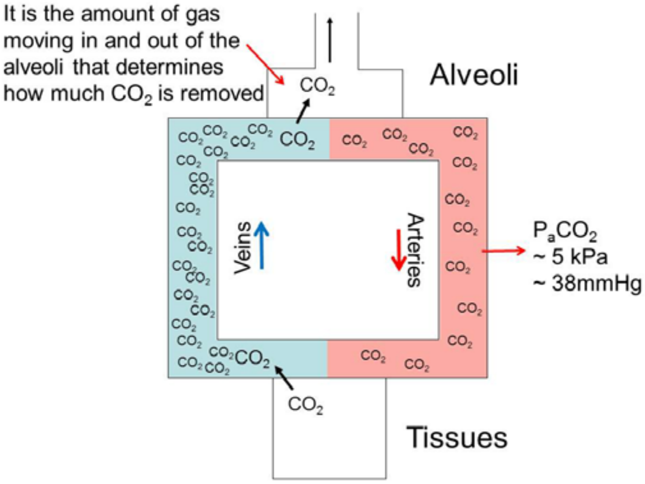


Figure 1. Depiction of the process of production and elimination of CO_2.

It can be deduced from Figure 1 that the production of CO_2 in tissues and its removal by the lungs are processes that must be balanced. If ventilation of the lungs is inadequate ('hypoventilation') CO_2 levels will increase, and if ventilation is excessive ('hyperventilation') then CO_2 levels will decrease. The process of balancing CO_2 elimination by the lungs with production by the tissues is mediated through control of ventilation by the respiratory controller in the brain stem. Although maintenance of adequate oxygenation would seem intuitively more important than CO_2 regulation, and although both hypoxia and hypercapnia do provoke the respiratory controller to increase breathing, it is the P_aCO_2 that is widely accepted as the primary effector. The respiratory controller indirectly monitors arterial CO_2 levels through sensing of the pH of the cerebrospinal fluid (which is directly influenced by P_aCO_2). If CO_2 levels increase then the respiratory controller will drive increased ventilation to remove more CO_2 and vice versa. The controller generally 'defends' a P_aCO_2 around 38 mm Hg ± 7.5 mm Hg (2SD) (5.1 kPa ± 1 kPa [2SD]), though as will be seen below, this can be disturbed in diving. This is a substantial oversimplification of a complex and incompletely understood process, but it is adequate for the purposes of this discussion.

The most common derangement of this system during diving is that there may be inadequate ventilation and an increase in P_aCO_2; a process often referred to as 'CO_2 retention'. The obvious question is 'what causes divers to hypoventilate thus allowing the P_aCO_2 to rise?' The answer is not simple or even fully understood, but a significant contribution to the process occurs because of the increase in the work of breathing that occurs during diving. Thus, in the following section we briefly consider the causes of increased work of breathing in diving.

Causes of Increased Work of Breathing in Diving

There are multiple factors that increase the physical effort required to move gas in and out of the lungs during diving.

Immersion effects

Immersion may cause changes in the mechanical properties of the lungs if the chest is exposed to a different external pressure than the pressure inside the airways. For example, consider a diver upright in the water using open-circuit scuba. The regulator supplies gas at a pressure equating to the ambient pressure at the depth of the second stage (mouthpiece). Since the diver's airways are connected to this regulator, the pressure inside the airways is therefore the same as the ambient pressure at the depth of the mouth. The lungs themselves (remember the diver in this example is upright) are slightly deeper than the mouth and they are therefore exposed to an external water pressure that is slightly higher than the pressure inside the airways. This difference in pressure 'across' the lung (the pressure within the airways being slightly less than the pressure on the outside of the lung) is called a 'negative static lung load' or 'hydrostatic imbalance'. The relative negative pressure inside the lung airways encourages blood to engorge the relatively distensible lung blood vessels, and this renders the lung stiffer than normal. Put another way, the lung's compliance is reduced meaning that more muscular effort would be needed to move the same amount of gas in and out. A negative static lung load also exists when a rebreather diver with a back-mounted counterlung is swimming in a horizontal position. In this setting, the airways are in continuity with (and contain gas at the same pressure as) the counterlung, which is sitting at a slightly shallower depth (and lower pressure) than the lungs themselves.

Static lung loads can vary according to the type of equipment (open- or closed-circuit), the position of the counterlung in the latter, and the orientation of the diver in the water. It is beyond the scope of this article to discuss the various combinations of circumstances that may arise. Suffice it to say that under some commonly encountered circumstances, static lung loads (and particularly negative static lung loads) can increase the work of breathing during diving as described.

Equipment-related resistance

The use of underwater breathing apparatus imposes an external resistance to breathing. It is intuitively apparent that this would be potentially important in a rebreather. In using a rebreather all of the energy required to propel gas through the hoses, various connectors, and the CO_2 scrubber, must be provided by the diver's own effort. In this regard, the design of the rebreather (and in particular considerations like the geometry of the gas flow path, diameter of hoses, and type of CO_2 absorbent canister) can make a substantial difference to the work of breathing. Not surprisingly, there are recommended standards for maximum work of in underwater breathing apparatus. Relevant standards and testing of rebreathers in this regard are discussed in more detail by Anthony (2009).

Gas density

One of the most important influences on work of breathing in diving is the increase in density of respired gas that occurs as depth increases. Since any underwater breathing apparatus will supply gas at ambient pressure, the density of the respired gas increases in direct proportion to depth. Increases in gas density result in a parallel increase in the resistance to flow of the gas through the diver's own airways, and in rebreather diving there is also the extra effort of moving dense gas through the hoses, connectors and CO_2 scrubber of the unit. Under these circumstances, the associated increase in the work of breathing can be substantial.

Another relevant phenomenon profoundly affected by gas density is a reduction in the maximal ventilation that can be achieved even when a diver is consciously attempting to move as much gas as possible in and out of the lungs. For example, in dry chamber experiments it has been shown that the maximum amount of air a subject can move in and out of the lungs in one minute is approximately halved (compared to the surface) at 100 ft (30 m, 4.0 ATA) (Camporesi and Bosco 2003).

This 'ceiling' on ventilation performance appears related to the physiological phenomenon known as 'dynamic airway compression', and it is explained as follows. During maximal breathing effort, the muscles of the chest wall and diaphragm create a positive pressure inside the chest in order to force gas out of the alveoli and outward through the airways as quickly as possible. However, as gas passes out along the airway, the pressure inside airway falls due to frictional forces of the gas on the airway walls. At some point during a forced exhalation this pressure drop inside the airway is sufficient that the raised pressure inside the chest exceeds the pressure in the airway, and the airway starts collapsing. This limits the outward gas flow through the airway, and this restriction on outward flow then becomes the limiting factor in how much gas can be moved in and out of the lungs each minute.

This actually occurs in air breathing at 1.0 ATA, but the limitation begins at such high flow rates that is does not significantly hamper work performance (except perhaps in extreme exercise). However, when breathing a dense gas underwater the resistance to flow is much higher and a significant pressure drop inside the airway as gas flows outwards occurs at much lower flow rates. Thus, the airway will begin to collapse at low flow rates, and this limits breathing to a much greater extent than seen during air breathing at 1.0 ATA. Indeed, it has been shown that if extremely dense gas is breathed, a diver might not be capable of moving much more gas in and out of their lungs than during normal breathing sitting at rest (Wood and Bryan 1969). Such situations would be unlikely to be encountered in properly planned dives, but it is possible (see below). A more detailed and illustrated explanation of this phenomenon can be found in the DAN Technical Diving Workshop Proceedings (Mitchell 2009).

Physiological Mechanisms of Hypercapnia in Diving

Having briefly considered the causes of increased work of breathing in diving, the discussion moves on to an explanation of how this increase in work may result in hypercapnia.

With reference to the earlier discussion of control of ventilation, it would be expected that if the P_aCO_2 began to rise (for example, when a diver starts to exercise and produces more CO_2), then the respiratory controller would automatically increase ventilation in order to remove more CO_2 and bring the P_aCO_2 back to normal levels. This is indeed the classically described ventilation response in experiments using very low resistance breathing equipment where the P_aCO_2 is forced to rise by introducing CO_2 to the inhaled gas so that no matter how much the subject breathes, they cannot return the CO_2 to normal. Under these circumstances, curves plotting end-tidal CO_2 (an indirect measurement of P_aCO_2) and ventilation typically show an approximately direct linear relationship.

However, there is some degree of inter-individual variability in the ventilation response to rising CO_2, and this can be markedly exaggerated if there is an unusual increase in the work required to increase ventilation (as is the case in diving). Under these circumstances, it is as though the respiratory controller is confronted with a choice: Either to perform the extra work required to maintain a normal P_aCO_2, or to avoid the extra work and allow the P_aCO_2 to rise. There appears to be a spread of individual responses between these two extremes. This is illustrated in Figure 2 which shows end-tidal CO_2 vs ventilation 'curves' for 15 subjects who were breathing on a rebreather circuit with no CO_2 scrubber in place (Deng et al. 2015). In this setting there was no removal of exhaled CO_2 and consequently there was substantial CO_2 rebreathing. The arterial CO_2 was forced to rise no matter how hard the subjects breathed. It is also contextually important that the diving rebreather used in this experiment imposed an increase in the work of breathing that was greater than normal. The Figure 2 'curves' are lines interpolated between points plotted from measurements of end-tidal CO_2 and ventilation made 30 s after starting to breathe and on termination of breathing on the circuit. All of these subjects voluntarily terminated breathing within a five-minute period citing 'shortness of breath' among their symptoms. The remarkable feature of the data is the variability in individual ventilation responses. Some subjects did not increase ventilation at all (indeed in some it actually decreased) whereas others exhibited a more classical linear increase in ventilation as the end-tidal CO_2 rose.

The implication of these data (and those of others that have examined the underlying mechanisms in more detail (Poon 1987; 1989)) is that in some divers at least, there is a tendency for the respiratory controller to prioritize the avoidance of respiratory work over maintaining the P_aCO_2 at normal levels when the work of breathing is increased. Put another way, during diving an increase in the work of breathing may provoke a 'naturally occurring flaw' in control of breathing such that the P_aCO_2 may rise simply because the diver does not breathe enough to eliminate the CO_2 that they are producing. This is the most plausible mechanism for the frequent finding of CO_2 retention in divers using underwater breathing apparatus (UBA), especially during exercise.

A second physiological mechanism for hypercapnia during diving relates to the potential for respiratory limitation by dynamic airway compression described above. It is plausible that if sufficiently dense gas was breathed a diver could find themselves in a situation where they would be unable to ventilate sufficiently to maintain a normal P_aCO_2 even at minimal levels of exercise, and even if they tried hard to do so. The principle of this mechanism is illustrated in Figure 3.

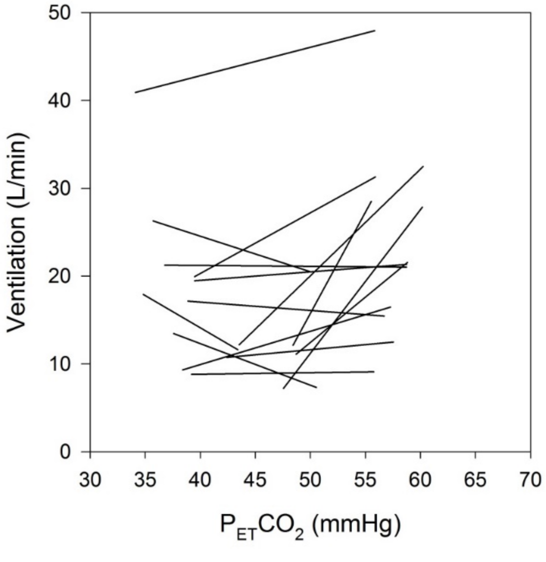


Figure 2. Indicative end-tidal CO_2 – ventilation curves for subjects breathing on a rebreather circuit with no CO_2 scrubber. Breathing was voluntarily terminated by the subjects when they developed symptoms of CO_2 toxicity (including a perception of shortness of breath in all cases). Each subject is represented by a straight line linking two paired measurements of end-tidal CO_2 and ventilation: the first made at 30 s after starting to breathe on the circuit, and the second on voluntary termination of the breathing period. $P_{ET}CO_2$ (end-tidal CO_2) is a conveniently measured approximation of the P_aCO_2. Reproduced with permission from Deng et al. (2015).

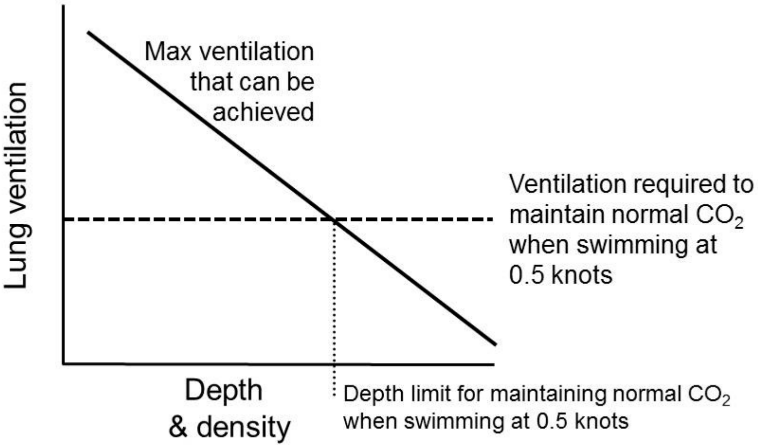


Figure 3. Notional depiction of the relationship between maximum possible ventilation and increasing depth and respired gas density. If the maximum possible ventilation falls below the ventilation required to eliminate the CO_2 produced (and therefore to maintain a normal P_aCO_2) at a given level of exercise, then the P_aCO_2 must inevitably increase. See text for further explanation.

In reference to Figure 3, the amount of ventilation (gas movement in and out of the lungs) required to keep the P_aCO_2 normal at a given level of exercise (nominally to swim at 0.5 knots) does not change as depth increases. However, as depth and the respired gas density increase, the maximum ventilation that can be achieved decreases because of the onset of dynamic airway compression at progressively lower flow rates through the airways. If the diver progresses deeper than a depth where they can produce the ventilation required to keep the P_aCO_2 normal, then the P_aCO_2 must inevitably rise. To make matters worse, the rising P_aCO_2 may trigger increased breathing effort which will only serve to produce more CO_2 because once dynamic airway compression occurs, no amount of extra effort will improve ventilation volumes. There is one published event in which there is reasonable supporting evidence for involvement of this mechanism, which occurred on a rebreather dive to a depth of 265 m (869 ft) (Mitchell et al. 2007).

For completeness, we observe that 'non-physiological' problems related to equipment (such as an absent, incorrectly installed or expired scrubber canister, or malfunctioning one way valves in the rebreather mouthpiece) are also potential causes of hypercapnia during rebreather diving. All of these result in some degree of CO_2 rebreathing, and if CO_2 is inhaled the diffusion gradient for elimination of CO_2 from venous blood to lung alveoli is diminished. If a large amount of CO_2 is rebreathed this can lead to a catastrophic impairment of CO_2 elimination with rapid development of symptoms of hypercapnia, but even a relatively small amount of inhaled CO_2 is potentially problematic because the associated impairment of CO_2 elimination will compound the physiological predispositions to hypercapnia described above.

Mitigation of the Risk of Hypercapnia During Rebreather Diving

At a practical level, the most important question arising from this discussion is 'what steps can be taken to mitigate the risk of hypercapnia during rebreather diving'? There are several possibilities.

Manipulation of static lung load

There is some evidence that a negative static lung load is the least desirable condition from a physiological perspective in rebreather diving, and that mildly positive static lung loads are best tolerated during hard work underwater (Thalmann et al. 1979). In a horizontal diver these conditions would be produced by back and front-mounted counterlungs respectively. However, choosing a counterlung configuration based primarily on concerns about static lung load may be ill-advised because the lung load will vary according to the diver's orientation in the water. For example, while a back-mounted counterlung would produce a negative static lung load in the horizontal position, it would be largely neutral in the upright position. In theory, over the shoulder counterlungs should produce the least extreme and least variable static lung load, but they have their own set of disadvantages such as cluttering the space around the diver's front and head.

Minimising equipment-related breathing resistance

All underwater breathing apparatus, including rebreathers, should be designed with the goal of reducing their external breathing resistance as much as is practicable. Other than choosing a device with good related design and testing characteristics there is little that divers can do in this regard. However, on a cautionary note, divers should take great care with making any modifications to a rebreather that might alter the geometry or resistance of the gas flow path. Common examples include departures from manufacturer-recommended grade of CO_2 absorbent material, the incorporation of extra oxygen cells for independent PO_2 monitoring, changing mouthpiece configuration, and changing the composition of any moisture pad material.

Consideration of gas density in diving planning

Most rebreather divers are very familiar with specialised dive planning strategies like calculating a maximum operating depth for a gas in order to avoid an unsafe inspired PO_2, or calculating an equivalent narcotic depth in planning the helium content of trimix to avoid unacceptable levels of nitrogen narcosis (Mitchell and Doolette 2013). In contrast, one almost universally overlooked dive planning strategy related to work of breathing is the use of gas density calculations to avoid breathing gases with unacceptably high density at depth. In no small part this situation prevails because there have been no definitive guidelines on acceptable gas density in diving.

There is a paucity of related data, though a recent analysis of a dataset of human testing records for UBA provides some potentially valuable insights upon which some preliminary guidelines can be based. Among other things, QinetiQ is a UBA testing house located near Portsmouth in the UK. Over some 20 years hundreds of manned test dives have been undertaken utilising ethics committee approved protocols which incorporate graded levels of underwater work for evaluating performance of a range open-circuit, semi-closed, and closed-circuit UBA. These dives have been conducted over depths ranging from 4 to 80 m (13 to 262 ft), using a range of gases including oxygen, air, nitrox and heliox. Throughout these tests a standard set of endpoints have been used to define 'dive failure' including: (any of) equipment or monitoring failure, diver unable or unwilling to continue because of dyspnoea (shortness of breath) or exhaustion, and an end-tidal CO_2 >8.5 kPa (64 mm Hg) over five consecutive breaths. The latter is indicative of significant CO_2 retention to a level associated with sudden incapacitation in the diving setting (Warkander et al. 1990).

Although this program of testing was not designed to specifically answer questions about tolerable gas density, the wide range of gas densities that were incidentally used has facilitated an evaluation of the proportion of work-loaded rebreather dive failures due to end-tidal CO_2 >8.5kPa stratified according to the gas density breathed. These data are reported in Figure 4. With the dual caveats that the trials were not specifically designed to answer this question and that the number of dives at the higher densities is comparatively small, there is a clear signal that near a respired gas density of 6.0 $g{\cdot}L^{-1}$ there is an upward inflection in the risk of dangerous CO_2 retention during working rebreather dives. A similar analysis of dive failures in open-circuit underwater breathing apparatus trials produced a virtually identical result.

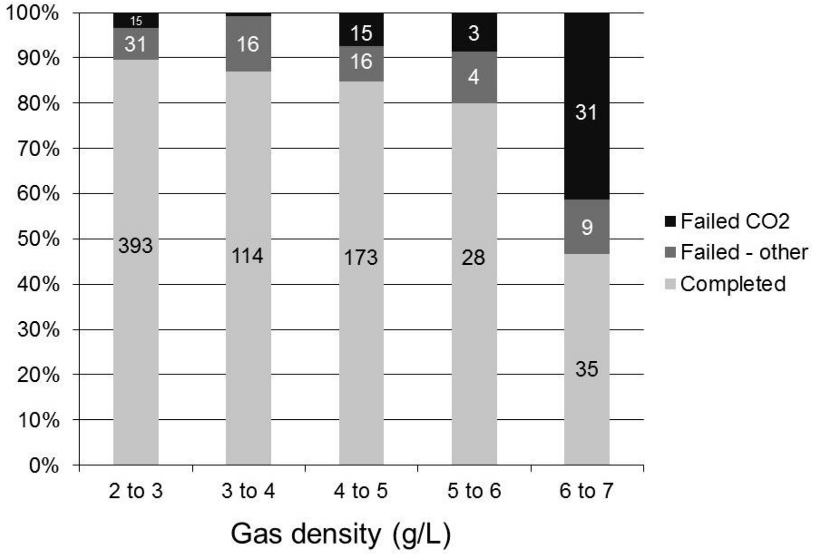


Figure 4. The proportion of rebreather test dives ending in failure due to an end-tidal CO_2 >8.5 kPa (black) and other causes of failure (dark grey) stratified by respired gas density. Figures refer to numbers of dives. At respired gas densities >6 $g{\cdot}L^{-1}$ there is a sharp increase in the risk of dive failure, with most failures being caused by dangerous levels of CO_2 retention.

For the purposes of planning rebreather dives and in the current absence of more definitive or contradictory data, it seems prudent to recommend an ideal maximum gas density of 5.2 $g{\cdot}L^{-1}$ (equivalent to air diving at 31 m [102 ft]) and an absolute maximum of 6.2 $g{\cdot}L^{-1}$ (equivalent to air diving at 39 m [128 ft]). Implementation of such a recommendation will require an appreciation of how to calculate gas density for a given respired gas at a given depth. Such calculations begin with knowledge of the density of air and the individual components of gas mixes at 1.0 ATA (Table 1).

Gas	Density ($g{\cdot}L^{-1}$)
Hydrogen	0.090
Helium	0.179
Nitrogen	1.251
Oxygen	1.428
Air	1.293

Table 1. Gas density in $g{\cdot}L^{-1}$ for common diluent gases, oxygen and air at 1.0 ATA. Data from Doolette and Mitchell (2011).

Calculation of the density of air at depth is a simple process of multiplying its density at 1.0 ATA by the ambient pressure at the target depth. For example, the density of air at 30 m (99 ft) is given by 1.293 $g \cdot L^{-1}$ x 4.0 ATA = 5.17 $g \cdot L^{-1}$.

Calculation of density for a mixed gas is achieved by using simple proportions to calculate the density of each component at 1.0 ATA, summing the components, and multiplying this sum by the ambient pressure in ATA at the target depth. For example, consider trimix 16:50 (16% oxygen, 50% helium, 34% nitrogen) intended for use at 70 m (230 ft) where the ambient pressure is 8.0 ATA. Calculating density for each component at 1.0 ATA we use the fraction of gas x its density at 1.0 ATA, thus, substituting in values from Table 1:

0.16 x density of oxygen (1.428) = 0.23 $g \cdot L^{-1}$
0.50 x density of helium (0.179) = 0.09 $g \cdot L^{-1}$
0.34 x density of nitrogen (1.251) = 0.43 $g \cdot L^{-1}$

The sum of the products of these calculations is 0.75 $g \cdot L^{-1}$ for density at 1.0 ATA. If this is then multiplied by 8.0 ATA for the ambient pressure at the planned depth we get 6.0 $g \cdot L^{-1}$. Therefore, in respect of gas density this would be an acceptable (but less than ideal) mix at this depth.

Moderating expectations of work capacity at depth

Unsurprisingly (given the above discussion) it is widely recognised among experienced divers that as depth increases there should be a corresponding moderation of expectation of work capacity. Hard work (with an inevitable increase in CO_2 production) is best avoided on a rebreather at any time, but this is particularly so at increased deep depths where the respired gas density is likely to be trending toward (or exceeding) the ideal limit. There are many practical strategies which help with reducing work at depth including exhibition of basic dive skills (such as maintenance of good buoyancy control and good trim/streamlining in the water), intelligent task planning, and the use of assistive technology such as diver propulsion vehicles. However, the use of such strategies is not a substitute for minimising the work of breathing in a UBA and strategic planning of gas density because events such as an emergency situation requiring extra work, or failure of a diver propulsion vehicle can occur unexpectedly.

Detection of CO_2 rebreathing

We earlier acknowledged the potential for CO_2 rebreathing to be caused by an absent, incorrectly installed or expired scrubber canister, or by malfunctioning one way valves in the rebreather mouthpiece. The strategies to prevent and detect such problems are issues of rebreather diving technology and practice rather than physiology. Nevertheless, for completeness, we will briefly discuss them there.

The cornerstone of preventing CO_2 rebreathing during use of a rebreather is meticulous adherence to manufacturer guidelines on both CO_2 absorbent duration and preparation of the rebreather before diving. Function of the mushroom valves in the rebreather mouthpiece should be checked every time the rebreather is assembled and the unit should not be used if the valves appear to be leaking. Great care must be taken with packing absorbent into the CO_2 scrubber canister to ensure that subsequent settling of the material does not result in a loose pack and channelling of gas through pathways of low material density. Similarly, the scrubber canister must be carefully installed in the rebreather avoiding any error that might result in gas bypassing the canister. Various rebreathers have easily avoidable but known vulnerabilities in this regard, and users must be aware of these.

As a final check of these good practices, rebreather divers are taught to conduct a five minute 'prebreathe' of the unit prior to entering the water. The prebreathe has multiple goals, but one of them (and the one upon which the five-minute duration is predicated) is the detection of symptoms of CO_2 toxicity should there be any error in preparation or assembly that allows rebreathing of CO_2. The efficacy of this strategy was recently tested in a randomised single blind study in which divers prebreathed a rebreather which either had a normal scrubber, a completely absent scrubber, or a partial failure of the scrubber allowing bypass of a significant amount of CO_2. The subjects were asked to terminate the prebreathe as they would in the real world if they developed symptoms of CO_2 toxicity. Twenty trials were undertaken in each condition. As expected, no diver terminated the prebreathe when breathing on a circuit with a normal scrubber. However, only 10% (2/20) were able to detect symptoms (and thus terminated) in the partial failure condition despite an inspired PCO_2 of 20 mm Hg. A much higher proportion (75%) detected the complete absence of the scrubber, but remarkably, 25% did not despite developing an end-tidal CO_2 greater than 60 mm Hg. Thus, it was concluded that while a prebreathe is a vital part of evaluating a rebreather before diving (for example, to check that the oxygen addition system is functioning), it cannot be relied upon to reveal problems with the CO_2 scrubbing function of the unit. Based on reports of a stressed or breathless appearance of some subjects who did not terminate during CO_2 rebreathing in the Deng et al. (2015) study, it could be concluded that peer observation of the prebreathe might improve its sensitivity. Whilst such a strategy might be applied successfully in a disciplined military or scientific diving setting, it is unlikely to be considered practical or executed diligently in 'mainstream' technical diving.

CO_2 sensors placed on the inhale limb of the rebreather circuit (downstream of the CO_2 scrubber) are a relatively recent innovation that represent a potential solution to the problem of detecting CO_2 bypassing the scrubber. These are only available on a small number of rebreathers at this time and there is limited experience with their use in the field. It is too early to make definitive recommendations on their use.

References

Anthony TG, Diving re-breathing apparatus testing and standards UK/EU perspective. In: Vann RD, Mitchell SJ, Denoble PJ, Anthony TG, eds. Technical Diving Conference Proceedings. Durham, NC: Divers Alert Network; 2009, pg. 218-36.

Camporesi EM, Bosco G. Ventilation, gas exchange, and exercise under pressure. In: Brubakk AO, Neuman TS, eds. Bennett and Elliott's Physiology and Medicine of Diving, 5th ed. Edinburgh, UK: Saunders, 2003: 77-114.

Deng C, Pollock NW, Gant N, Hannam JA, Dooley A, Mesley P, Mitchell SJ. The five minute prebreathe in evaluating carbon dioxide absorption in a closed-circuit rebreather: a randomised single-blind study. Diving Hyperbaric Med. 2015; 45: 16-24.

Doolette DJ, Mitchell SJ. Hyperbaric conditions. Comprehensive Physiol. 2011; 1: 163-201.

Mitchell SJ, Cronje F, Meintjes WAJ, Britz HC. Fatal respiratory failure during a technical rebreather dive at extreme pressure. Aviat Space Environ Med. 2007; 78: 81-6.

Mitchell SJ. Respiratory issues in technical diving. In Vann RD, Mitchell SJ, Denoble PJ, Anthony TG, eds. Technical Diving Conference Proceedings. Durham, NC: Divers Alert Network; 2009, pg. 12-37.

Mitchell SJ, Doolette DJ. Recreational technical diving part 1. An introduction to technical diving. Diving Hyperbaric Med. 2013; 43: 86-93.

Poon CS. Ventilatory control in hypercapnia and exercise: Optimization hypothesis. J Appl Physiol.1987; 62: 2447-59.

Poon CS. Effects of inspiratory resistive load on respiratory control in hypercapnia and exercise. J Appl Physiol. 1989; 66: 2391-99.

Thalmann ED, Sponholtz DK, Lundgren GEG. Effects of immersion and static lung loading on submerged exercise at depth. Undersea Biomed Res. 1979; 6: 259-90.

Warkander DE, Norfleet WT, Nagasawa GK, Lundgren CE. CO_2 retention with minimal symptoms but severe dysfunction during wet simulated dives to 6.8 atm abs. Undersea Biomed Res. 1990; 17: 515-23.

Wood LDH, Bryan AC. Effect of increased ambient pressure on flow volume curve of the lung. J Appl Physiol. 1969; 27: 4-8.

QUESTIONS AND DISCUSSION

AUDIENCE MEMBER: What is that depth again?

SIMON MITCHELL: It is not a depth. It is a density. So there are multiple ways you could achieve a particular gas density. You could have a light gas at a very deep depth or a heavier gas at a shallow depth. Irrespective of the depth the important thing is the gas density. Depth (or more correctly ambient pressure) is relevant in that it determines density for a given respired gas, but it is not relevant to these results.

JEFF BOZANIC: Did you measure PCO_2 during the tests for all your subjects?

SIMON MITCHELL: Yes.

JEFF BOZANIC: What was the highest level you were able to measure?

SIMON MITCHELL: The normal level of inhaled CO_2 is zero. It went up to over 50 mm Hg. By the end of a five-minute prebreathe with no scrubber our subjects had an end-tidal CO_2 of around 8.5 kPa, over 60 mm Hg, who had no idea (Deng et al. 2015). Unbelievable, is it not? Even with substantial ventilation increases a lot of these divers did not know. In terms of the ventilation increase, the tidal volume increased more than the rate.

DAVE CONLIN: Two questions. One, the separation between your counterlungs and your actual lungs, do you get to a point at depth where that difference in pressure because it is a small difference in the overall pressure, that your body is physiologically experiencing, is inconsequential? If you are at 33 ft (10 m), 25 cm is a lot different in pressure.

SIMON MITCHELL: I see, you are asking is there context with depth in determining a static lung load? No -- 20 cm of water is always 20 cm of water, no matter where you are in the water column.

DAVE CONLIN: My other question is if your body is a CO_2 retainer and your body does not care about the CO_2 it is retaining, so to speak, what is the problem?

SIMON MITCHELL: That is a good question. I did not think to mention it because high CO_2 becomes a problem in everyone once it reaches a certain point. The trouble is that CO_2 retainers do not see it coming. Dan Warkander and Barbara Shykoff at NEDU have done a lot of work on this. What they see with CO_2 retainers is that CO_2 creeps up during exercise at depth with an elevated breathing resistance. The divers are peddling away underwater indicating "I am fine." Then, all of a sudden, they either pass out or stop responding to hand signals. They pass a threshold and the lights go out. So, eventually it happens to everyone. The non-CO_2 retainers get more symptoms as the CO_2 levels go up. They sense it and are more aware of the problem, and under normal circumstances would be more likely to stop what they are doing and rest to prevent the CO_2 rising any further. That is the trouble with CO_2 retention. The diver may be unaware of it so does not respond in the way they should, which is to stop and rest and get their breath back.

DAVE CONLIN: One final comment about the prebreathe. If you have a temp stick, you are getting a lot of secondary information, not physiologically based, that shows a value of doing a prebreathe, seeing that your stacks warming normally, and that your PO_2 is dropping and rebounding.

SIMON MITCHELL: Agreed. If it takes five minutes to activate your temp stick and that is what you like to see, then you should do a five-minute prebreathe. But our message is that divers should not kid themselves that completing the prebreathe is verifying that they have perfectly functioning scrubber.

MARK KEUSENKOTHEN: So once a CO_2 retainer, always a CO_2 retainer?

SIMON MITCHELL: That is a great question. There is good news and bad news in that category. There is some evidence that diving actually teaches you to be a CO_2 retainer. None of that data actually applies to rebreather divers specifically. And I would not be surprised if it is less of an issue with rebreather divers. The theory is that it is the breathing discipline that you impose on yourself when you are an open-circuit diver to try to conserve gas which teaches you to be a CO_2 retainer. There is some evidence in that regard. There is also some evidence that you can train yourself not to be one. There is one paper published by a group at Buffalo which showed that respiratory muscle training can actually lower the tendency to retain CO_2. So, there is some evidence, if preliminary, in both directions.

> *Pendergast DR, Lindholm P, Wylegala J, Warkander D, Lundgren CE. Effects of respiratory muscle training on respiratory CO_2 sensitivity in scuba divers. Undersea Hyperb Med. 2006; 33(6): 447-53.*

DAVE PENCE: In terms of correct mix gas selection for deep rebreather driving, you said that rather than actually having to do the actual gas density calculations, it is adequate to simply select a mixture that gives you an appropriate equivalent narcotic depth?

SIMON MITCHELL: No, the opposite actually. I said that by looking after your equivalent narcotic depth, you do not automatically end up with a gas of sufficiently low density. You may need more helium for gas density purposes than you need for equivalent narcotic purposes. It should be part of dive planning; make sure your PO_2 and your END are going to be okay. Then when you think you have chosen your gas, calculate the gas density at the target depth and make sure that is okay as well. If it is not, bump the helium up appropriately.

DAVE PENCE: They have a practice among some rebreather divers simply to use Heliair as the diluent, which always leaves you with an oxygen to nitrogen ratio of 1 to 4. Does that tie equivalent narcotic depth closer to breathing resistance than actually mixing.

SIMON MITCHELL: There will be a sweet spot somewhere where it does, but it will not apply across the entire depth range. I think it is an individual calculation that probably should be done for most dives. Over time you will start to get used to what works at what different depths.

JOHN BRIGHT: Is there any information that CO_2 retention will increase your sensitivity to other inert gas narcosis, i.e., you increase your CO_2 retention and the threshold at which PN_2 and PO_2 will have an additive narcotic effect decreases?

SIMON MITCHELL: Unfortunately, CO_2 retention is synergistic with nitrogen narcosis. There is enough evidence to believe that there is a synergy between the two; that is they are actually worse than the sum of their parts. CO_2 retention is bad for narcosis. CO_2 is a very narcotic gas. There was even a proposal at one stage that CO_2 could be used as an aesthetic agent because if you breathe enough of it, it will render you unconscious. It never caught on. But certainly it is worse for narcosis. The other thing that you mentioned is the interaction between CO_2 retention and oxygen toxicity. This interaction probably accounts for the higher risk of oxygen toxicity when divers are in the water compared to sitting in a chamber breathing oxygen through a low resistance system. In the water we all probably retain a little bit of CO_2, especially if we are working hard or our breathing resistance is high. For a given PO_2 this increases the risk of oxygen toxicity because CO_2 dilates the cerebral blood vessels. So blood flow to the brain is much higher when CO_2 is elevated, and this increases oxygen delivery and thus the oxygen tension in the brain. There are very good experimental data demonstrating this.

> *Lambertsen CJ, Ewing JH, Kough RH, Gould R, Stroud MW. Oxygen toxicity: arterial and internal jugular blood gas composition in man during inhalation of air, 100% O_2 and 2% CO_2 in O_2 at 3.5 atmospheres ambient pressure. J Appl Physiol. 1955; 8: 255-63.*

So, CO_2 retention is a risk factor for narcosis and a risk factor for oxygen toxicity. It is an important gas that people do not understand well enough. Some of what I have been explaining is quite complex, but it is an important gas to understand because it has far-reaching effects in a lot of what we do.

KARL HUGGINS: In the five-minute prebreathe with the failed loop is the CO_2 retention enough to change physiological pH, say, in the saliva where it is something that could be measured by litmus or some other type of pH detector?

SIMON MITCHELL: Good thought. If you did an arterial blood gas on most people when they had an end-tidal CO_2 of 64 mm Hg, they will all have a respiratory acidosis. Whether in a five-minute period that translates into a change in saliva pH is another thing entirely. Intuitively I would say probably not, but I would not bet my house on it. It is a good thought. It is easy to test exactly the way you suggested it.

PHIL SHORT: Could the condition and the same thing happen with open-circuit?

SIMON MITCHELL: CO_2 retention can definitely happen on open-circuit (but obviously not because of CO_2 rebreathing as in a rebreather). CO_2 retention can occur if the breathing resistance is increased for any reason, especially if combined with exercise. This may be less likely on open-circuit because the breathing resistance is often lower on a good open-circuit set. One of the things I did not share is one of the other disadvantages of a negative static lung load which can also occur on open-circuit. If you have a negative pressure in your airways, it increases the risk of dynamic airway compression. This is because falling pressure along the airway is more likely to promote airway collapse if you have got a negative static lung load and there a relatively negative pressure in the airway. Returning to rebreathers, theoretically, if a diver with a back-mounted counterlung flipped over onto his back to create a positive static lung load might help splint the airways open. Emphysema patients get the same problem at atmospheric pressure because they have got so little elasticity in their lungs. You watch them breathing and see that they create a back pressure in the airway by exhaling through pursed lips so it stops the airways collapsing. This is why a positive static lung load is slightly better for hard exercise because the positive pressure splints the airway open. I am digressing; CO_2 retention on open-circuit could certainly happen if you breathe a gas dense enough that it significantly increases work of breathing or you get dynamic airway compression which limits lung ventilation.

RICHARD PYLE: You referred generically to more breathing. What is the difference between increasing tidal volume versus increasing respiratory rate versus increasing both to maximally achieve that?

SIMON MITCHELL: The answer is that minute volume, that is, the product of tidal volume and respiratory rate, makes a difference in removing CO_2. The only caveat is that in diving we have an extra little bit of deadspace in our mouthpiece. The average rebreather mouthpiece has 50-80 mL of increased deadspace, which brings our total deadspace to just over 200 mL. So if you really want to increase ventilation of your alveoli, you need to increase tidal volume more than rate. A very high number of tiny breaths will just ventilate the deadspace.

RICHARD PYLE: Even if you just count the extra deadspace from diving equipment, it will lean you toward tidal volume?

SIMON MITCHELL: Absolutely right.

RICHARD PYLE: So I guess both.

SIMON MITCHELL: Both are important.

Scientific Rebreather Standards

Elizabeth Kintzing[1], Marc Slattery[2]

[1] University of New Hampshire, School of Marine Sciences and Ocean Engineering, Durham, NH 03824
ek@unh.edu
[2] University of Mississippi, Department of BioMolecular Sciences, Oxford, MS 38677
slattery@olemiss.edu

Abstract

Arguably, one of the most important recent advances in scientific diving has been the inclusion of rebreathers as a tool to enhance science. Rebreathers offer increased safety relative to deep reef research and archeological resource surveys conducted on open circuit by virtually eliminating the gas consumption pressure associated with deep open circuit dives, and they have increased the quality of fish censuses due to the reduced noise. As rebreathers have evolved over the last decade, scientific rebreather standards have not kept pace. Specifically, three discrete scientific diving agencies within the US have adapted three independent sets of rebreather standards. These standards include consideration for training (i.e., classroom and practical experience) and proficiency, as well as standards related to the equipment and the operational aspects of scientific rebreather diving. Here we examine the current standards in place, and provide recommendations relative to improving technologies, and also relative to minimum training and proficiency dives so that the three agencies might better collaborate moving forward.

Keywords: closed-circuit, decompression, oxygen, regulation

Introduction

Rebreathers have become increasingly common in the scientific diving community in recent years; approximately 50 AAUS members currently include rebreather dives in their annual reports, and government divers (i.e., National Park Service [NPS], United States Geological Survey [USGS] and National Oceanic and Atmospheric Administration [NOAA]) also utilize this advanced scientific diving mode. For example, scientists have found that the constant PO_2 of rebreathers provide the requisite safety to access mesophotic reef communities and/or submerged archeological resources, and that the lack of bubbles facilitates more accurate censuses of marine fishes on reefs. However, rebreather standards have not kept pace with the changes in rebreather technologies (e.g., oxygen, semiclosed-, and closed-circuit rebreathers); the AAUS rebreather standards were written over 10 years ago. Here we examine the existing rebreather standards and provide direction for the future.

Methods

This paper reviewed as many scientific rebreather standards that were available to the authors. Unfortunately, no standards were identified from Europe. The majority of agencies queried reported using American Academy of Underwater Sciences (AAUS), National Park Service (NPS) and National Oceanic and Atmospheric Administration (NOAA) rebreather standards. Data presented here represent these standards as they exist today.

Results

Current rebreather standards

Training Standards: As a prerequisite for rebreather training AAUS (2013) and NPS (2014) divers must have full scientific diver status, be certified to 100 fsw (30 msw), have 50 open water dives, and nitrox certification. In contrast, NOAA (2014) requires full scientific diver status, certification to 130 fsw (40 msw), 100 open water dives, and nitrox certification. For each agency, rebreather training involves stepwise certifications to increasing depths. Successful completion of rebreather training only certifies an individual to dive on the unit they trained on, and under similar environmental conditions.

Rebreather Classroom Training: 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, must be included in the classroom training. Rebreather specific information will include: system design and operation, pre-dive setup and testing, post-dive break down and maintenance, oxygen exposure and decompression management, dive operations planning, problem recognition and management.

Practical Training: Rebreather system calibration and operation checks, absorbent canister use and management, gas analysis and pressure checks, breathing loop assembly and one-way valve testing, pre-dive breathing to assess system integrity, buoyancy control and system monitoring at all phases of the dive, bailout procedures for self and buddy, and proper system maintenance, must be included in the practical training. Rebreather training includes minimum hours of underwater time, prior to certification under supervised conditions (Table 1).

Table 1. Minimum rebreather training requirements for AAUS, NPS, and NOAA

Type	**Pool/Confined Water**	**O/W Training**	**O/W Supervised**[1]
Oxygen	1 dive, 90 min	4 dives, 120 min[2]	2 dives, 60 min
Semiclosed-circuit	1 dive, 90-120 min	4 dives, 120 min[3]	4 dives, 120 min
Closed-circuit	1 dive, 90-120 min	8 dives, 380 min[4]	4 dives, 240 min

[1] The number of post-training open water supervised dives for NOAA is one-half of the dives reported for AAUS and NPS. All other standards are identical.

[2] Dives should not exceed 20 fsw (6 msw).

[3] 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.

[4] Total underwater time (pool and open water) of approximately 500 min. The 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.

Additional requirements for the use of extended range, decompression, and mixed gas rebreather diving include the approval of the institutional diving control board (DCB), on a case-by-case basis, along with additional training. As a prerequisite for these advanced rebreather techniques the diver must have 25 h and 10 dives in 100-130 ft (30-40 m) range for decompression training. For trimix training the diver must have 50 h using the rebreather, as well as staged decompression methods, and at least 12 dives requiring decompression on the rebreather with at least four of those dives near 130 fsw (40 msw) (AAUS and NPS) or near 150 fsw (46 msw) (NOAA).

In order to maintain proficiency AAUS and NOAA standards requires one dive every eight weeks, or six dives per year, while NPS requires 24 dives (with a minimum of 18 h underwater) per year.

Equipment Standards: All rebreathers utilized in scientific diving must be approved by the relevant DCB, and it is clear that these standards vary broadly between institutions. Acceptable rebreathers should comply with quality assurance and quality control (QA/QC) protocols as outlined by ISO 9004 standards and verified by a recognized authority (i.e., CE, US Navy, Royal Navy, etc.). The units will have documentation detailing unmanned and manned testing by an independent test facility. Documentation will include: operational depth range and temperature, breathing gas mixtures, gas supply duration as a function of exercise level and depth, absorbent duration as a function of exercise level, depth, and temperature, accuracy and precision of all readouts and sensors as a function of exercise level, depth and temperature, battery duration, likely failure modes and mean time between failures. The rebreather must include a complete instruction manual, as well as a maintenance log.

Minimum equipment on rebreathers include: a mouthpiece assembly that allows sealing of the breathing loop from the external environment when not in use, an automatic gas addition valve, manual gas addition valves, and an alternate life support capability (i.e., open-circuit bailout or redundant rebreather) (AAUS 2013; NOAA 2014; NPS 2014). Semiclosed-circuit rebreathers must be equipped with at least one manufacturer-approved oxygen sensor, while closed-circuit mixed gas rebreathers (CCRs) must have a minimum of three independent oxygen sensors. In addition, CCRs should have two independent power supplies, redundant on-board electronics, and life support systems. Currently, AAUS requires all CCRs to have a minimum of three independent oxygen sensors, while NPS and NOAA require CCRs to have an oxygen sensing system that has been demonstrated to be reliable through empirical testing, such as with a minimum of three unvalidated oxygen sensors, or with an active validation system that has two or more oxygen sensors, or other oxygen sensing technology with similarly demonstrated reliability.

Operational Standards: All agencies agree that the use of rebreathers implicitly requires that dives comply with manufacturer requirements (i.e., maintenance, modifications to the system, and specific design limits), and that all dives comply with applicable logistics to open-circuit scuba dives (AAUS 2013; NOAA 2014; NPS 2014). In addition to the standard dive plan components required by the agencies, rebreather dive plans must also address the following: specific rebreather used, type of scrubber material, composition and volume of gases, and detailed bailout procedures. The dive buddy should be familiar with the specific rebreather as it relates to potential assistance/rescue of the rebreather diver. Some institutions require buddies to be on the same rebreather, while others allow any rebreather or even open-circuit buddies. If the dive buddy is using open-circuit, that individual should carry enough open-circuit gas to get the pair to the surface (and the rebreather diver should be able to assist the open-circuit buddy with enough open-circuit gas to get that individual to the surface). The DCB must approve the method of decompression for any given dive plan and application. Check-sheets should be used pre- and post-dive, and maintenance logs should be kept for each rebreather unit; these documents (electronic or paper) will be filed and maintained as part of the equipment record. Additional equipment required by a few institutions include: mouthpiece retention devices, hard-wired communications, and/or full face masks.

Redundant life support systems must be designed to get the diver safely to the surface, including required decompression stops, in the event of failure of the primary rebreather. These systems can vary depending on the depth and time profile of the rebreather diver, but they typically involve: open-circuit bailout cylinders (either carried, pre-positioned at depth, or delivered by surface support personnel), and/or redundant rebreathers carried by the diver. About half of the scientific divers are required to carry enough gas to bailout alone, while the remainder utilize a team bailout approach (pers. comm., Jeff Godfrey). A few organizations require on-board open-circuit bailout valves. Consumables (e.g., batteries, oxygen sensors, CO_2 absorbent) shall be maintained, tested, and replaced according to manufacturers' specifications. Long-term storage of CO_2 scrubber shall be in a cool, dry location, in a sealed container. Some agencies require the use of a CO_2 detection device. The breathing loop, including mouthpiece, hoses, counterlungs, and CO_2 canister should be disinfected periodically as indicated by the manufacturer, and/or prior to use by another diver.

With respect to oxygen exposures, AAUS, NOAA, and NPS are in agreement; the F_IO_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, and the PO_2 setpoint shall not be lower than 0.4 ATA or higher than 1.4 ATA. The maximum operating depth shall be based on the F_IO_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. 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). Finally, oxygen rebreathers shall not be used at depths greater than 20 fsw (6 msw), and the breathing loop must be adequately flushed with pure oxygen prior to the dive and prior to ascent at the end of the dive to avoid hypoxia.

Discussion

As rebreather diving becomes more common within the scientific community, and as agencies continue to collaborate, it becomes increasingly important that standards are consistent and verifiable. Moreover, these standards need to be broad enough that multiple agencies are encompassed by the requirements such that reciprocity is a seamless issue. For example, differences occur in training prerequisites between AAUS, NPS, and NOAA, as well as post-training proficiency and supervision. However, it is likely more important that the post-training supervision and proficiency numbers are more similar rather than the hours leading up to rebreather certification. Rebreather qualification by recognized diving agencies carry fairly rigorous training standards in theory, pool and open water work. The difference between a recreational rebreather diver and a scientific rebreather diver is the scientific diving course the latter divers take. Thus, supervision of recently qualified rebreather divers, as they learn to multi-task the safety aspects with the scientific needs, is important. Similarly, proficiency numbers should be looked at from the standpoint of minimal annual dives needed, and the need for an increasing number of work-up dives prior to research when rebreathers have not been used for extended periods of time.

Training: As more rebreathers become available, many of which have simple configurations requiring less task loading, rebreather standards need to be flexible enough to encompass the manufacturer-suggested training hours for those units. However, scientific diver status on these units will still require an adequate number of work-up dives so that the newly certified rebreather diver has the depth qualification and skills requisite for the planned scientific application; this will likely need to be determined on a case-by-case basis within each scientific diving program. Coordination of the skills training relevant to the specific scientific application should include the scientific diver, the diving safety officer (DSO), and members of the DCB and/or diving community versed in rebreathers and that scientific application. During this training, the scientific diver will require supervision by experienced rebreather divers, and progressive task loading relevant to the scientific application, until they are deemed competent in skills at the representative depth.

Proficiency: Rebreather diving proficiency standards must also be flexible enough to meet the needs of scientific divers with year-round access to research sites and those who conduct a single annual expedition. Current standards vary between agencies, although all seem to recognize that rebreather diving may be sporadic. Regardless of the number of dives to maintain certification (i.e., AAUS and NOAA require six per year vs NPS which requires 24 per year), any rebreather diver who does not meet a minimum number of dives within a certain period (usually eight weeks) must complete work-up dives prior to conducting scientific activities that increase task loading. Most dive programs recommend one to three dives at increasingly deeper depths before scientific activities are initiated at that depth; again this standard will likely vary on a case-by-case basis given the relative experience of the scientific diver, and the type of scientific diving to be completed.

Equipment: Rebreather testing information may be proprietary, and not readily available to diving programs, despite the fact that many rebreather standards require this information. It is possible that the scientific diving organizations (e.g., AAUS, NOAA and NPS) may be able to access some of this information and pass it along to the independent dive programs. At the very least, each program should remain cognizant of recalls and/or accident reports relative to the rebreather units they work with, as this information may have direct bearing on the future use of these units. In addition, rebreather manufacturers often come up with updated plug-and-play instruments (e.g., CO_2 sensors), and/or software upgrades, that potentially increase the safety of the units. As scientific divers upgrade their units, they must demonstrate proficiency in the improved units via classroom theory, practical handling, and work-up dives prior to resuming normal scientific diving practices. Again, it is imperative that the scientific diver and the diving program remain cognizant of recalls and/or accidents relative to the update. Perhaps less intuitively, whenever a new scientific instrument is being used in the field, the scientific rebreather diver should plan on work-up dives with that instrument in the pool and/or at shallower depths until they are competent for the new/additional task loading.

One example of advances in rebreather technology that have exceeded existing standards relates to the oxygen sensing systems. Current AAUS standards (2013) require three independent oxygen sensors, however, several new rebreathers make use of two, or even one, oxygen sensor, or sense more than one gas at a time. Newer validation technologies, as opposed to the older voting logic, makes fewer oxygen sensors a reasonable approach. However, dive programs must update their standards to recognize these new options. We recommend that AAUS adopt standards that allow for use of these newer rebreathers. A recent suggestion would provide dive programs with the opportunity to meet an AAUS standard while determining their own internal needs. The new AAUS standard might read: *"CCR's must have gas sensing systems demonstrated to be reliable through empirical testing, and validated by a recognized independent testing authority."* (pers. comm, David Pence).

Operational: There are several operational considerations relative to rebreather safety that warrant inclusion in standards manuals. There are several types of scrubber available to rebreather divers, primarily differing in granule size. These have manufacturer suggested usage duration that will vary depending on the depth used, the breathing frequency, and the physical condition of the dive (i.e., temperature). Most rebreather divers follow the simple rule of changing scrubber after a set period of time (e.g., three hours of use), or, in some cases, when a temperature stick indicates a reduction in scrubber reaction, but this is too simplistic given the many factors that can affect scrubber duration. Thus rebreather dive plans should include consideration for scrubber replenishment given the unique conditions of any given research site. Likewise, there are movements to reduce the PO_2 inspired from the current standard of 1.3 ATA to 1.2 ATA or less (pers. comm., Jeff Godfrey). While there is clearly a modicum of safety associated with reduced PO_2 limits, there are also situations where the higher PO_2 might be advantageous, such as during resting decompression at or above 20 fsw (6 msw). Standards that provide some flexibility could facilitate optimal dive planning.

Bailout requirements also vary significantly among the rebreather community; from every diver carrying enough gas to get him or herself out of the water, to relying on team or community bailout. In the latter case the team may collectively carry enough gas to get 1.5 divers to the surface from the most extreme point in the dive. Recent rebreather options include onboard open-circuit bailout regulators that allow divers to switch from closed-circuit to open-circuit (i.e., bailout) with the turn of a lever. If used the diver must ensure annual servicing of the open-circuit onboard bailout regulators (as required for all life support gear), and should test the system at depth periodically, and they should maintain proficiency in solo or group bailout approaches.

Checklists also vary between dive programs, and likely cannot be easily codified as detailed standards given the diversity of rebreathers currently being used by the scientific diving community. Instead, each dive program should advocate the use of checklists specific to the rebreathers in use. Another safety factor that has been discussed as a potential standard is the use of full-face masks (to prevent a seizing divers from losing the mouthpiece). While this does provide an added level of rebreather diver safety, full-face masks can be costly, difficult to wear, and increase the potential for other problems (e.g., CO_2 buildup). A simpler alternative is the use of mouthpiece retention straps. Regardless of choice, rebreather divers should be cognizant of the signs and symptoms of O_2 toxicity, and should include options for handling a seizing diver in their dive plan. Finally, as suggested by rebreather manufacturers, appropriate disinfectants should be used regularly to clean the hose and counterlungs; this will prevent the growth of potentially harmful microbes (e.g., *Legionella*) in the breathing space that could result in serious pulmonary infections.

Conclusions

It is clear that rebreathers provide a significant tool for the scientific diving community, and the use of this tool must involve standards that maintain the safety of the scientific divers. Rebreather standards, like the field, should reflect the dynamic and multi-disciplinary nature of the marketplace.

References

American Academy of Underwater Sciences [AAUS] Standards for Scientific Diving Manual, Section 12: Rebreather Standards; 2013.

National Oceanic and Atmospheric Association [NOAA] Scientific Diving Standards and Safety Manual; Section 10: Rebreathers; 2014.

National Parks Service [NPS] Standards for Scientific Diving Manual, Chapter 3 & 4: Rebreather Training and Certification Requirements; 2014.

QUESTIONS AND DISCUSSION

JEFF BOZANIC: I am going to make one comment here. These standards are probably reasonable for where we are right now, but you need to be thinking about the fact that 10 years from now you may have people that come in here that have never been open water certified. So they come in and learn on rebreathers as their starting platform for learning to dive. And we do not want to get so rigid in our thinking that we forget that this is going to be evolving as we go through time.

LIZ KINTZING: Standards should get reviewed and revised every couple years. But what you are saying is that we should leave them a little bit more open?

JEFF BOZANIC: You may want to include some dialogue that we recognize these will evolve through time so that people get the idea and the understanding that this is a working document. Because a lot of times we write stuff down and it becomes stone. And our intent is not to make it stone.

LIZ KINTZING: We do want to make sure that what we have in writing is what we are doing and that we can move forward on things that we learn. The AAUS standards were written long ago and there is definitely stuff we do in the field that is different from what might be in the manual.

DAVE PENCE: I think one of the things that we struggled with when we wrote it originally was as with any other application of diving in science, there is a broad range of intent. Does the diver simply want to be quiet and work very shallow? There is no reason why somebody needs to have a 100-ft (30 m) certification if they are going to be out chasing sea otters or doing shallow work on oxygen rebreathers. But I think the overall perception was that we were writing a document for people who were expecting to fairly quickly move into extended ranges. And so as that philosophy changes or as that application changes, then, as was pointed out, it is probably very appropriate to start looking at different prerequisites. That being said, what you really need to do is write it so that you evaluate what that person's intent is going to be as to what the prerequisite should be.

STEVE SELLERS: To Dave's comment, I know that when NPS went through the evolution of their standard related to rebreathers, we looked out there to see what other people were doing. And when we see check boxes in other standards that list a dive requirement, a time requirement, a depth requirement, that kind of thing, it frames the conversation for the boards as to, well, it is there. And it goes back to your point about minimum standards. It is there. And I echo what Dave is saying here, that the idea -- because in practice -- we have got this standard in place, but in practice we require a program that wants to go into rebreather diving, they have to give us a proposal. And we review the proposal and look at their program and then say yes or no.

LIZ KINTZING: That is an important point. Whenever somebody says they want to be certified to 100 ft (30 m). My question is why? Do you have work there? What is your purpose for going down there, not just because you want to be certified, not just because you want to use a rebreather.

PHIL LOBEL: I think part of this is probably a mix too, not only in terms of the intent, but the independence of the observer, the scientist going out and doing the work. So if you are talking about somebody starting on rebreather or working in shallow water, my question would be are they being supervised by someone who is really a competent leader in that technology that is watching them versus somebody who is like me taking a rebreather, going out with the team and diving on a reef somewhere and diving independently.

DAVE PENCE: It is partially correct to say in terms of the training, the training dive numbers. I remember vividly the discussion that Doug Kesling and I had when we were trying to come up with this. It was Doug's point, and a very good one, that once they get the training, the scientist still needs to understand how to apply that technology. And that is really the whole idea of the supervised dives, to mentor them in the application of this technology to their science. This is not included in the training agency standards.

LIZ KINTZING: No. That is why I said that is what we as a science community require. And, basically, what I did after I got my rebreather certification. Our end goal was to stop doing deep open-circuit dives. But that took us several years to do because in New Hampshire I am not using my rebreather very much.

AUDIENCE MEMBER: Build significant experience on the unit before they became significantly task loaded. It seemed excessive to our users, but after they made the investment in that 45-50 h of dive time post-training, they were far more efficient and productive in the field.

LIZ KINTZING: Proficiency standards. I think NOAA and AAUS require one dive every eight weeks or six per year. NPS requires 24 per year or 18 hours. Many OMs will have in their manual, as we do, that before you go on any mission if you have not kept up your eight dives or one every eight weeks, then you do workup dives beforehand. Do people think this is a reasonable approach or we actually need to dive once every two months or two every month for the rebreather?

JEFF BOZANIC: I think that is perfectly reasonable. That is no different than a requalification course. It is a refamiliarization. If you are not going to keep up a certain minimum level of experience, the amount of workup dives that you do is going to be a function of how much prior experience you have and how long it has been since you had that prior experience.

STEVE SELLERS: For Park Service it is both 24 dives and a minimum of 18 h. The other little piece that I do not know if you picked up on or not in our standard, when we get a new rebreather program in the Park Service, they are required to be on rebreathers exclusively for the next year -- they convert to rebreathers for a year after the supervised dives and have to have special permission if they want to use open-circuit equipment because we want them to develop the muscle memory and think in terms of PO_2 instead of just looking at pressure gauges.

SIMON TALBOT: We have one guy whose lab uses the rebreathers only, and they do a month a year and we pretty much do a full workup before that, all the bailouts in the pool.

LIZ KINTZING: So it sounds like everybody is okay with the workup system if you are not diving every eight weeks or twice a month before your missions. Shallow shakedown dives is what I usually call them.

DAVE PENCE: We all in this room know that the nature of science is there are going to be extended periods where you are in the laboratory or in the library rather than in the field, which is going to naturally require that we have these long periods of inactivity, even among dive officers from time to time based on seasonal or administrative requirements. I think that the workup requirement after an extended period is more significant than the number of dives per year.

LIZ KINTZING: I agree. The next one is going into like extended range, you know, using decompression and helium-based gases. Most of the agencies require at least 25 h on the rebreather, 10 dives in the 100-130 ft (30-40 m) range before you can actually start doing decompression on the rigs. At least that is what in the standards. And if you want to move up to trimix or helium-based gases, they require 50 h on the rig and 12 dives with decompression. And four of them are supposed to reach 130 ft (40 m). NOAA requires 150 ft (46 m) exposures. Are these reasonable? Too little? Too much?

RICHARD PYLE: Part of the problem is you have such a heterogeneity in the individual divers involved. It is hard to come up with a single rule.

LIZ KINTZING: But for a minimum.

RICHARD PYLE: When you think about them in terms of minimum, yes.

JEFF BOZANIC: Those are like bare minimums in my mind. I would much prefer to see probably double those numbers in each one of those in a general case, particularly if you are looking at people that you expect to be working underwater during these dives as well.

LIZ KINTZING: Minimum equipment standards. At least at AAUS institutions, the DSOs and DCB can figure out whether someone is ready to move forward. These are just equipment requirements. Before you get started with AAUS, NPS and, I think, NOAA, the board has to approve what unit you are using. There can be a mix of standard rules and institutional norms.

JEFF BOZANIC: Do you think that the Mark VI without the optional manual addition valves would be useable in a program?

RICHARD PYLE: I am probably biased. I should not answer that question. It depends on the context. If you are going to try to be quiet in five feet (two meters) of water, do you really need manual gas additions? You are practically on an oxygen rebreather at that point. It depends on context. It is too hard to say one unilateral standard.

JEFF BOZANIC: My point is if we are going to have a standard in there, you want to leave yourself the flexibility to be able to utilize other equipment that is out there. And I do not see a problem with the Mark VI without the manual addition valves for some applications within science. And there are others where you would want to have that. My comment would be that looks to be a 10-year-old standard when there were no units out there without manual addition valves.

RICHARD PYLE: What you say I agree with.

LIZ KINTZING: Some of the newer recreational rigs coming on the market, do they have manual addition or are they all just automatic?

RICHARD PYLE: Does Kevin's new semiclosed one have manual?

JEFF BOZANIC: It only has one gas cylinder because it is a nitrox-based system.

RICHARD PYLE: I will add one more thing, to close out this little conversation. There was a very specific reason for not having manual oxygen and that is born from experience. Which is that in the recreational paradigm there are circumstances where that tool can be more harmful than beneficial for someone who is not thinking straight. In other words, we found that divers can sometimes be adding oxygen when they do not mean to be adding oxygen and get themselves into trouble. And we found that the control system was much better than the diver in maintaining PO_2. So in that context, we felt that the O_2 manual oxygen addition was more of a liability than an asset.

JEFF BOZANIC: And my argument is that the same is true in the scientific diving community.

RICHARD PYLE: It may well be, yes.

LIZ KINTZING: After your talk yesterday, if your machine is better than you at rebreather diving, then we are all in trouble. Okay. Let us move on to bailouts. Everyone completing the survey said that, except the oxygen rebreather guys, said they carry offboard bailouts. And then when we get to offboard bailout, we get to like the extended range where you might be using a lot of different bailouts. There were two schools. About 55% responded that everyone carries their own gas. Team bailout was allowed by about 45%. And then there was the integrated bailout valve. Relatively few institutions require them.

DAVE PENCE: These statistics are on what people are currently doing. What was the wording on open-circuit bailout? I believe it is simply that the diver must have reliable access to open-circuit bailout.

LIZ KINTZING: Yes.

LIZ KINTZING: Any thoughts on whether we should change scrubber stuff?

STEVE SELLERS: I think the goal is for folks to look at their written standards and then at what divers in their programs are actually doing.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

Operational Considerations for the Use of Closed-Circuit Rebreathers in Scientific Diving Research

Douglas E. Kesling

Aquatic Traning Systems, LLC, 5701 Wood Duck Circle, Wilmington, NC 28409
dkesdiver@aol.com

Abstract

Electronically controlled, closed-circuit rebreather (eCCR) diving operations are becoming increasing popular among the scientific diving community. Due to the complexity of the diving equipment and the necessary oversight for launching a successful field operation, special care combined with a specific knowledge base by users is required for the effective use of this evolving diving technology. This paper will illustrate and highlight the important steps in establishing operational guidelines and procedures for safe and successful conduct of deep diving operations using closed-circuit rebreather technology for scientific research and exploration.

Keywords: closed-circuit rebreather, diving safety, eCCR, risk management

Introduction

Science drives the system. It has become increasingly important that diving equipment technology and procedures evolve to meet the needs of wet diving marine scientists as they begin to explore new ocean realms that were inconceivable in the past 20 years, due to limitations with early self-contained underwater breathing apparatus. As a result of these improvements and the recent developments in state of the art electronically-controlled, closed-circuit, mixed gas rebreather technology (eCCR), technological advancements have created many new opportunities by extending diving capabilities for *in-situ* research diving. Resource managers, scientific institutions, government entities, university dive programs and other stakeholders are now seeking new research data from undersea locations which have not been physically obtainable or explored in the past. Many scientific diving programs are now beginning to establish technical diving facilities, with expertise and capabilities to allow the marine scientist to safety access these new underwater research areas of interest. Because of the extreme nature and style of this diving exposure, it is essential that a thorough operational plan be established to ensure safe diving operations and to help reduce associated risks for participating personnel by providing sound operational guidelines. The overriding goal for this level of extreme, technical diving with eCCRs is that the diving become second nature for participants, which allows diving scientists to focus on their scientific research and data collection at hand.

Research Proposal Development

The formative steps in a successful rebreather program begin with the initial research proposal development. Commonly discussed topics include: funding and grant agencies, under whose oversight the diving will be conducted; do the program divers have the necessary diving skills and background for the proposed work; and will the institution seek out others to help develop the program's operational diving components. Depending under whose auspices the project will be conducted, there will likely be issues of partnerships, institutional liability, workers compensation coverage, the use of volunteer divers and contracted vendors which will need to be discussed and considered. It is important that the project has adequate funding to support all aspects of the research initiative. An operational plan will be an essential component of this proposal and, as such, be as complete as possible so that all necessary resources can be contributed to the project development and proposed work (Sherman et al. 2010).

Minimum Standards

When developing a minimum standard as an operational plan for decompression diving using eCCR, the following aspects would need to addressed and highlighted:

Overview - scope of project

Institutional liability is a big consideration in the early decision making and planning phase of a diving operation. A clear picture needs to be drawn as to who has ultimate authority for conduct of the research diving mission and the responsible parties for sign-off of the diving operational plan. The Diving Safety Officer (DSO), with guidance from the Diving Control Board (DCB), will likely require a formalized dive plan to review and approve before diving activity commences. This proposal may also be vetted through the institution's risk management officials and their environmental health and safety office.

Personnel qualifications

Divers may be part of the sponsoring institution, or come to the project from another institution as a visiting diver or through a diver reciprocity agreement. Under a reciprocity agreement, the divers remain protected for injury and liability from their home institution. Careful consideration must be taken when selecting team members to participate in eCCR operations. Certifications to use the equipment or even scientific expertise should not be the deciding factors in qualifying personnel for deep eCCR operations. Personnel should possess a high degree of discipline in their approach to eCCR diving and a willingness to work as a team member, leaving ego out of the equation. These factors are sometimes lacking in many individuals who are drawn to 'technical diving' and can be invaluable when assembling a safe and productive diving team. This selection process normally starts at the institutional level with the DCB and DSO, and it is important to have open and honest communication with all parties to lay the groundwork for a successful collaboration.

Team selection – Science Team (Dive Backgrounds & Experience)

AAUS standards (2013) include the following training prerequisites for rebreather use:

1. Active scientific diver status, with depth qualification sufficient for the type, make, and model of rebreather, and planned application.
2. Completion of a minimum of 50 open water dives on scuba.
3. 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.
4. Nitrox training. Training in use of nitrox mixtures containing 25-40% oxygen is required. Training in use of mixtures containing 40-100% oxygen may be required, as needed for the planned application and rebreather system. Training may be provided as part of rebreather training. (http://www.aaus.org/diving_standards).

Certification and authorization for diving personnel will come from the institutional DSO and DCB. The panel will outline proficiency requirements for the divers to maintain skill levels and will likely require team members, once rebreather certified, to maintain proficiency with their eCCRs by diving them on a regular basis.

Equipment

Equipment General Requirements (AAUS 2013):

1. Only those models of rebreathers specifically approved by DCB shall be used.

2. 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.

3. Unit performance specifications should be within acceptable levels as defined by standards of a recognized authority (CE, US Navy, Royal Navy, NOAA, etc.).

4. 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.

5. 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 which 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

A complete instruction manual is required, fully describing the operation of all rebreather components and subsystems as well as maintenance procedures.

It is important to select a rebreather system which has a high level of support from the manufacturer. Bench testing procedures, annual maintenance criteria, essential equipment upgrades, off-the-shelf spare parts, a system for communication and notification of product recalls, and allocation of consumables are all considered necessary.

The dive team shall keep maintenance records in the form of a maintenance log. The unit maintenance shall be up-to-date based upon manufacturer recommendations. If the maintenance cannot be conducted in-house, then it will need to be out-sourced to a reputable entity or vendor.

Breathing gas and gas management

Key components of breathing gas and gas management include standardized cylinder color coding and labeling for ease of cylinder identification, maximum operating depth (MOD) markings, approved gas delivery components for all planned depths, adequate hose lengths for gas sharing, compatible quick disconnects for gas sharing/reserve gas plug-ins, mouth-piece preventers for inadvertent gas switching of hyperoxic gas mixes on all open-circuit scuba. All gases used for diving must be of breathing quality. All breathing mixtures to be used for diving shall be analyzed for oxygen and helium content using an oxygen/helium analyzer. Gases must test within acceptable parameters for oxygen content as specified in the manufacturer's rebreather guidelines. It is the responsibility of each diver to confirm and verify in writing the oxygen/nitrogen/helium content of his/her cylinder(s) prior to commencing diving, and to verify the following:

- PO_2 cutoff depth (MOD) and appropriate gas mixture(s) to be used for each phase of the dive;
- Planned maximum depth and bottom time for the dive; and
- Availability of adequate gas volumes as determined by review of cylinder sizes and pressures.

Divers shall carry sufficient gas to complete all phases of the dive including descent, on-the-bottom, ascent and decompression independent of surface support. Additionally, sufficient gas shall be carried to complete in-water decompression for the next deeper depth and bottom time planned. These gases may be carried/staged by individual divers in a fashion to support team, eCCR diving.

Oxygen used for diving shall meet or exceed the purity levels for Medical (USP) or Aviator Grade oxygen. Compressed air used with oxygen concentrations greater than 40% or when used in the preparation of nitrox breathing mixtures with greater than 40% oxygen as the enriching agent, shall meet or exceed CGA Grade E standards.

Gas filling and gas transfer capabilities shall be a part of the operational plan and additional equipment must be considered for the safe and effective transfer and mixture of dive gases.

Manning requirements

Buddymanship of at least two divers is required at all times. No solo diving is permitted. In-water support divers and additional safety divers positioned topside may be deemed necessary, depending on the complexity of the operation. Additional personnel topside should include dive tenders for dressing out the dive team, and a dive supervisor for the oversight of all dive and deck operations.

Dive team configuration

Establishing a dive team roster is an essential first step in considering the primary tasks of the underwater team members. It is important that with a large, mixed team of divers, that divers still are assigned individual diver team members of two to three team members, so there is no confusion as to who must respond to an emergency either topside or for underwater emergency responses.

Topside support

Additional personnel topside is always an added bonus for the rebreather dive team. Familiarity with rebreathers and all operational procedures are a must have skill.

Dive supervision

A dedicated dive supervisor is essential for all rebreather diving activities. This is not to say that this individual cannot take part in the dive rotations, but depending on the complexity of the rebreather operation, serving in this role topside might be the best decision. An alternate supervisor can be placed in this topside role should the lead dive supervisor choose to dive. In any event, this person should be a highly skilled and experienced diver who can oversee the dive team, ensure compliance and completeness of deck checklists, perform the pre-dive briefing for all hands, oversee the final prebreathe-phase checklist for the dive team, interface with vessel captain and crew, and coordinate/oversee any emergency in-water or topside response for a diving emergency. He or she will be asked to make critical go or no-go decisions on a daily basis, which may include diver performance and fit-to-dive standards, vessel operations, equipment issues, weather conditions and ability to effect a rescue when called upon.

Initial training

Open-circuit, mixed-gas technical dive training and associated experience prior to rebreather certification has proven an effective precursor to gain enhanced diving skills for eCCR diving operations. A three-tiered approach beginning with level one, an entry level course, followed by level two incorporating advanced decompression skills and techniques; and finally level three which completes the mixed-gas and extended range aspects of the eCCR training progression.

Additional training and proficiency eCCR dives should occur on a frequent and regular basis and should include all team members, support staff and dive supervisor(s) when possible.

Dive planning

The dive plan shall include, but not be limited to, the following elements:

- Overview of operations
- Goals, objectives, and science tasks to be accomplished
- Description and location of dive site
- Names, affiliations, roles/responsibilities, and qualifications of all participants
- Schedule of operations
- Description of equipment and facilities
- Logistical arrangements and considerations
- Normal and emergency diving procedures
- In-water support
- Surface signaling devices/techniques – notification of bottom team status
- Recovery of samples
- Dive accident management plan
- Supporting documents, permits, and forms

Load lists

A detailed load list is a valuable tool for ensuring that all essential equipment, spares and consumables are available to the rebreather divers and other support team members. Completion of a pre-mission supply load list (Table 1) has proven highly effective in the success of launching a field diving operation.

Decompression strategy

Decompression is easily conducted with the use of multi-level, multi-gas decompression computers. Modern rebreather technology incorporates real time PO_2 measure in the calculation of decompression status on the unit's onboard, integrated dive computer measuring actual PO_2 levels for inert gas uptake and elimination. Decompression algorithms currently in use include the *Buhlmann* and VPM-B models. Selectable gradient factors on the computer also appears to be an important tool when programming additional safety measures into the prescribed decompression model. The PO_2 is normally, set at a 1.3 ATA for eCCR operations, but could be set at an alternative PO_2 level based on the decompression strategy employed. Back-up, offboard dive computers serve as a reliable means to monitor decompression information. It is suggested that the back-up computer closely match the eCCR's decompression calculation information as well. Normally, a fixed PO_2 is set at 1.25 ATA for an offboard unit, providing a bit of safety margin for the diver in the event there are problems with the onboard decompression computations in real time, which are following the unit's actual PO_2 readings. Additionally, back-up paper decompression tables are usually prepared and carried by eCCR divers in the event of a failure of primary and secondary decompression instrumentation, or if the diver is forced off the loop (bailout) and must decompresses with open-circuit scuba. Current multi-gas, multi-level decompression computers allow the user to switch quickly from closed-circuit (CC) to open-circuit (OC) mode in the event of an eCCR bailout on the fly.

Daily dive procedures

Before each dive evolution, all personnel must assemble and receive a thorough daily dive briefing. The following are essential components of this exercise:

- Pre-dive brief (all hands)
    - Dive team – Buddy team assignments; planned dive (appropriate gases for all depths)
    - Dive site identification and any potential hazards
- Dive parameters
    - Depth and time considerations with planned decompression information
    - S-drills upon descent
    - Buddymanship
    - Communication throughout dive
    - Safe & controlled ascents
- Science objectives and assigned sample tasks, sample recovery
- In-water support (standby open-circuit or eCCR divers – as required)
    - Discussion of what the in-water support might consist of
    - Depth and decompression status limitations – all divers
- Contingency planning (bailout gases for the appropriate depths and quantity)
  Emergency procedures review
- Dress-out – final deck checklist – prebreathe sequence on the eCCR

Checklists - field reports - data management

During Rebreather Forum 3 held in Orlando, Florida in May 2012, a consensual, guideline document with recommendations for eCCR use was developed by participants (Mitchell 2014). It was decided by attendees that due to the complexity of rebreathers compared to traditional open-circuit diving, the following should be adopted to reduce the risk of user errors with rebreathers:

1. Manufacturers produce carefully designed checklists, which may be written and/or electronic, for use in pre-dive preparation (unit assembly and immediate pre-dive) and post-dive 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
2. Training agencies and their instructors embrace the crucial leadership role in fostering a safety culture in which use of checklists by rebreather divers becomes second nature (Tables 2-4).

Table 1

Pre-Mission: Supplies (Load List) (*Developed for the AP Valve Inspiration eCCR*)

- ☐ Spare CCR part and components (unit-specific)
    - DSV mouthpieces/tie wraps
    - Oxygen add valve
    - Diluent add valve
    - Manual inflator (diluent service kit)
    - Manual inflator (oxygen service kit)
    - Filter (scrim) service kit, if required
    - DSV mouthpiece service kit
    - Canister O-ring and/or seal kit
    - Convoluted hose service kit
    - Flow stop valve – GC3
    - O_2 sensor connector
    - Spare submersible pressure gauge (SPG) – oxygen
    - Spare SPG – diluent
    - Spare low pressure whip for onboard addition

- ☐ Sofnolime (8-12) mesh or _____________; ____/_____ Exp. Date
- ☐ Spare batteries for CCR 6 volt lithium or other; ____/_____Exp. Date
- ☐ Spare oxygen cells – CCR (type) ≤12 months from manufacture
- ☐ Disinfectant and mixing container/spray bottle
- ☐ O_2 analyzer __________ (DIN flow adapter)
- ☐ He analyzer __________ (DIN flow adapter)
- ☐ O_2 analyzer cell (spare)
- ☐ He analyzer cell (spare)
- ☐ Spare batteries (D, C, 9 volt, AAs)
- ☐ Christo lube - MCG 111 Lubricant
- ☐ Misc. Viton O-ring kit
- ☐ Tool kit
- ☐ Battery/Cell multi-meter tester
- ☐ AC bench counterlung forced air dryer system
- ☐ Oxygen resuscitator unit – (O_2 kit) ________ cylinder(s) full
- ☐ First aid kit

___________________________________ ___________________

Completed by Date

Table 2

Pre-Mission: Diver Checklist (*Developed for the AP Valve Inspiration eCCR*)

☐ Oxygen cylinders – _____ cu ft. _________ psig ___________ % O_2
☐ Diluent cylinders – ______cu ft. _________ psig _____/_____/_____ %O_2/He/N_2
☐ Spare O_2 cylinders – _____ cu ft.
☐ Spare diluent cylinders – _______ cu ft.
☐ Offboard diluent cylinder _________ psig _____/_____/_____ %O_2/He/N_2
☐ Offboard deco 1 cylinder _________ psig _____/_____/_____ %O_2/He/N_2
☐ Offboard oxygen cylinder _________ psig ___________ % O_2
☐ OB diluent regulator and submersible pressure gauge (SPG)
☐ OB oxygen regulator and SPG
☐ OB deco 1 regulator and SPG
☐ Dive computer
☐ Line reel(s)
☐ Surface marker buoy(s) (SMBs)
☐ Cutting devices (knife)
☐ Dive light
☐ Dive mask(s)
☐ Fins and booties
☐ Exposure suit
☐ Dive weights
☐ Dive gear bag

______________________________________ ____________________
Diver Date

Table 3

Pre-Dive: Dive Planning (*Developed for the AP Valve Inspiration eCCR*)

Date: ___________________________
Location: ______________________
Diver: __________________________
Dive Buddy: ____________________

Verify Dive Plan

- ☐ Depth ____________ fsw
- ☐ Bottom time ___________ min
- ☐ Diluent ______/_______/_______ %
  O_2 He N_2
- ☐ Oxygen ____________ O_2 %

- ☐ Offboard oxygen ____________ O_2 %
- ☐ Offboard diluent ______/_______/_______ %
  O_2 He N_2
- ☐ Offboard deco 1 ______/_______/_______ %
  O_2 He N_2
- ☐ PO_2 setpoint _________ ATA (bottom phase)
- ☐ PO_2 setpoint _________ ATA (deco phase)
- ☐ NDL/TTS ____________ min
- ☐ CNS % ______________
- ☐ UPTD/OTU % ______________

Pre-Dive: Bench Set-Up/Test (*Developed for the AP Valve Inspiration eCCR*)

Date: __________________
Diver: _________________

Gasses Analyzed

Onboard

- ☐ Oxygen cylinders - 19 ft^3 ___________ % O_2
- ☐ Diluent cylinders – 19 ft^3 _____/_____/_____ %O_2/He/N_2

Offboard

- ☐ Offboard diluent cylinder _________ psig _____/_____/_____ %O_2/He/N_2
- ☐ Offboard deco 1 cylinder _________ psig _____/_____/_____ %O_2/He/N_2
- ☐ Offboard oxygen cylinder _________ psig ___________ % O_2

- ☐ Install cylinders
- ☐ Oxygen cylinders - 19 ft^3 _________ psig
- ☐ Diluent cylinders -19 ft^3 _________ psig
- ☐ Check intermediate pressures, pre-mission or at least once monthly
  - Diluent regulator ___________(bar) (9.0-9.5 bar)
  - Oxygen regulator ___________ (bar) (7.5-8.0 bar)
- ☐ Connect low pressure supply hoses
- ☐ Test diluent and oxygen add valves

Breathing Loop (*Developed for the AP Valve Inspiration eCCR*)

- ☐ Pack scrubber canister
    - Canister time remaining _______________ min
- ☐ Lube canister lid and spacer O-ring
- ☐ Install temperature stick
- ☐ Closed scrubber lid and install into shell
- ☐ Attach oxygen supply hose
- ☐ Route hoses and cables through housing
- ☐ Close shell cover
- ☐ Confirm operation of non-return valves in mouthpiece and reconnect to T-pieces
- ☐ Check DSV function
- ☐ Check mouthpiece and direction of air flow through loop (exhalation towards divers right shoulder)
- ☐ Conduct a negative loop pressure test (per manufacturer specifications) (no dive, if not passed)
- ☐ Conduct a positive loop pressure test (per manufacturer specifications) (no dive, if not passed)
- ☐ Set counterlung OPV in "Dive Position"

Electronics (*Developed for the AP Valve Inspiration eCCR*)

- ☐ Switch on electronics handset and proceed to dive mode
- ☐ Follow handset prompts
- ☐ Verify proper computer function
- ☐ Verify function of head-up display (HUD)
- ☐ Verify correct calibration of oxygen sensors
- ☐ Verify battery levels are sufficient for planned dive (at least two bars)
- ☐ Test O_2 manual add valve
- ☐ Test diluent manual add valve
- ☐ Flush with diluent and check for low oxygen warning display and buzzer
- ☐ Test auto-air and BC power inflator
- ☐ Test automatic diluent valve (ADV)
- ☐ Close mouth piece
- ☐ Secure gasses
- ☐ Turn off electronics

_____________________________________ _______________

Diver Signature Date

Table 4

<u>Prebreathe Sequence – DON Rebreather</u> (*Developed for the AP Valve Inspiration eCCR*)

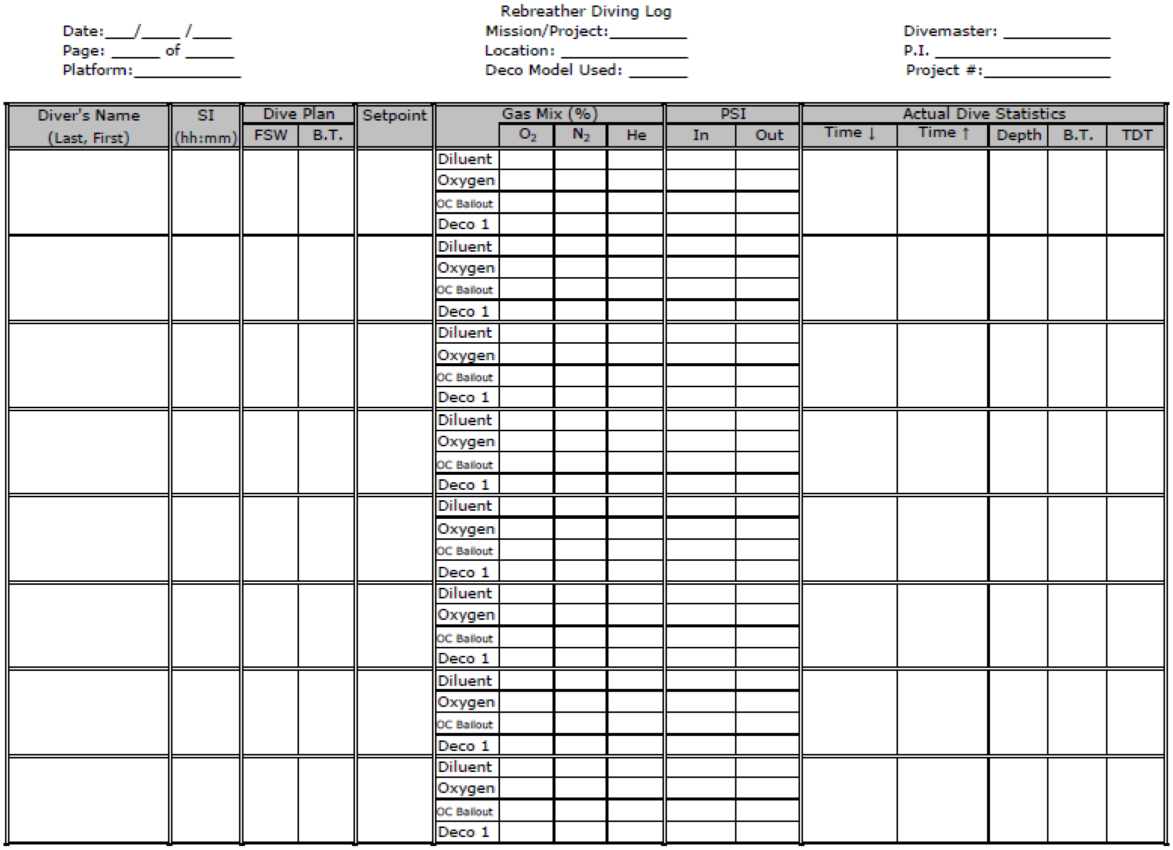
- ☐ Turn on gasses
- ☐ Verify fill pressures for onboard oxygen and diluent
- ☐ Check bailout and offboard deco gas pressures
- ☐ Turn on electronics
- ☐ Follow pre-dive prompts on handset
- ☐ Verify high and low O_2 setpoints
- ☐ Low _____ ATA
- ☐ High _____ ATA
- ☐ Verify AUTO setpoint
- ☐ Verify active gradient factors for planned decompression schedule
- ☐ Prebreathe for three minutes, ensure mouthpiece is fully open!
- ☐ Verify correct diluent gas selected for planned dive (handset)
- ☐ Ensure PO_2 drops on exhalation
- ☐ Check for slow reacting cells
- ☐ Confirm O_2 control system properly maintains PO_2 (listen for solenoid function
- ☐ Confirm temperature stick operational
- ☐ All straps and counterlung fastened to harness
- ☐ Display monitoring – CCR diver will check PO_2 display every three minutes
- ☐ Bailout cylinders will be attached to diver
- ☐ ***"Do not use CCRs with underwater tools that produce significant vibrations, strong jet output or other hydrodynamic forces that might impact the operational controls on the rebreather."***
- ☐ Do a bubble check with buddy upon descent (Diver)
- ☐ Verify setpoint change for bottom phase of the dive (Diver)

_______________________________________ __________________
Dive Supervisor/Signed Dated

Dive log

The use of well-organized dive log sheets is encouraged and can assist the dive team in the pre-dive, dive and post-dive phases of the data gathering process by organizing and recording all vital dive safety information. They can be a valuable tool for post-dive statistical reporting, incident review and risk mitigation (Table 5).

Table 5



Rebreather Diving Log

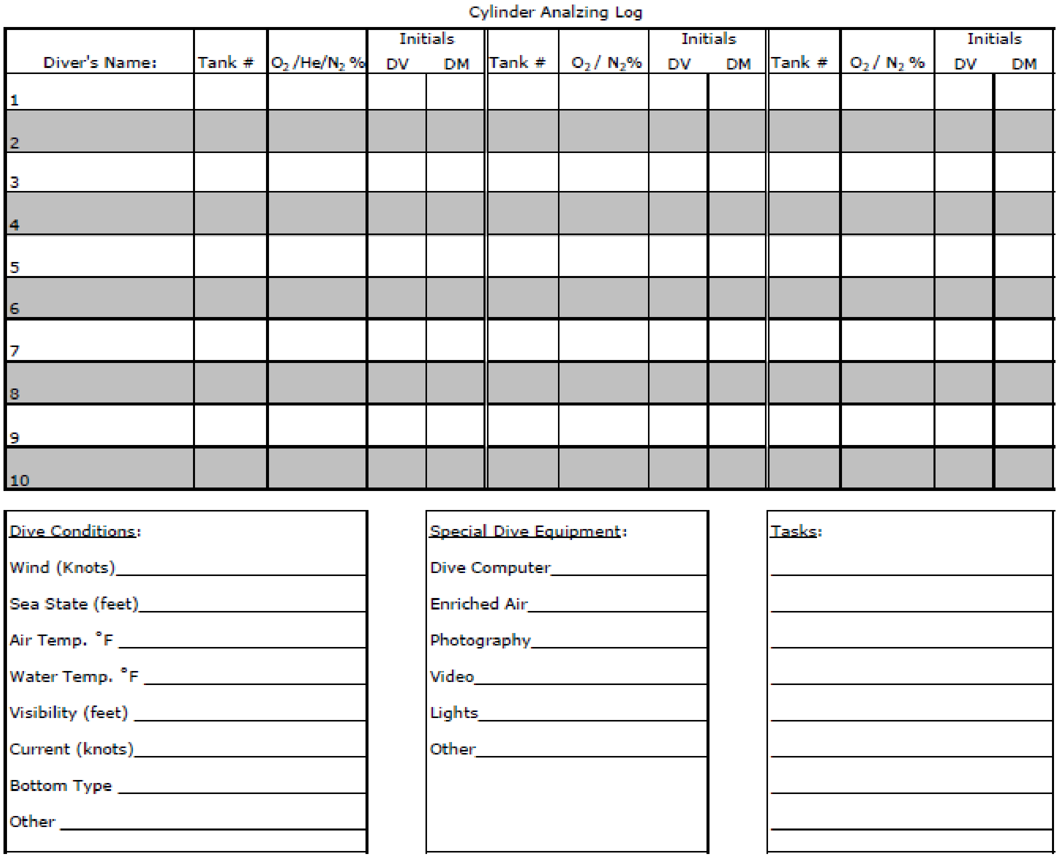
Date:___/____ /____
Page: _____ of _____
Platform:___________

Mission/Project:_________
Location: _____________
Deco Model Used: ______

Divemaster: ___________
P.I. __________________
Project #:_____________

Diver's Name (Last, First)	SI (hh:mm)	Dive Plan		Setpoint	Gas Mix (%)				PSI		Actual Dive Statistics				
		FSW	B.T.			O_2	N_2	He	In	Out	Time ↓	Time ↑	Depth	B.T.	TDT
					Diluent										
					Oxygen										
					OC Bailout										
					Deco 1										
					Diluent										
					Oxygen										
					OC Bailout										
					Deco 1										
					Diluent										
					Oxygen										
					OC Bailout										
					Deco 1										
					Diluent										
					Oxygen										
					OC Bailout										
					Deco 1										
					Diluent										
					Oxygen										
					OC Bailout										
					Deco 1										
					Diluent										
					Oxygen										
					OC Bailout										
					Deco 1										
					Diluent										
					Oxygen										
					OC Bailout										
					Deco 1										
					Diluent										
					Oxygen										
					OC Bailout										
					Deco 1										

PAGE 1 of 2 – Dive Log



Cylinder Analzing Log

Diver's Name:	Tank #	O_2 /He/N_2 %	Initials		Tank #	O_2 / N_2%	Initials		Tank #	O_2 / N_2 %	Initials	
			DV	DM			DV	DM			DV	DM
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												

Dive Conditions:
Wind (Knots)
Sea State (feet)
Air Temp. °F
Water Temp. °F
Visibility (feet)
Current (knots)
Bottom Type
Other

Special Dive Equipment:
Dive Computer
Enriched Air
Photography
Video
Lights
Other

Tasks:

PAGE 2 of 2 – Dive Log

Contingency planning

Out of gas – Breathing Loop Failure – Bailout procedures

> Divers should always be prepared to bailout, if it is determined that the breathing loop can no longer perform safe operations and support life. Special consideration should be made to have the breathing loop outfitted with a bailout valve (second stage - BOV) incorporated into the diver select valve (DSV), for immediate gas switching to open-circuit breathing gas without removing the eCCR mouthpiece. Additionally, some manufacturers have had success with full-face masks as an added feature of their eCCR units, which allows incorporating underwater communications for added safety, while maintaining an air space for the diver in the event of unexpected unconsciousness.

Aborted dive procedures

> Unexpected events occur while diving. Suspend the dive and begin a controlled ascent with completion of all required decompression obligations. An aborted dive should be a planned event without concerns or issues affecting the overall diving operation. The saying goes, *"Safety first, science second!"* A thorough post-dive debrief should be conducted by all participants after all dives, and in particular with an aborted dive event. There should be a discussion of lessons learned and specific mitigating events to help reduce the likelihood of similar situations reoccurring, affecting future dive operations and next deployments. In most cases, dives can be

reattempted after a thorough examination of the situation, ensuring all pre-dive parameters are met for a second attempt. If there is a major safety concern related to the dive event(s), then it is wise to have a safety stand-down period to reevaluate the procedures, equipment or other variable factors such as vessel-of-opportunity performance, weather-related concerns/sea states or individual diver readiness.

Omitted Decompression

Omitted decompression can be problematic for the divers and might lead to serious physiological consequences. Attempts should be made immediately to reestablish a missed decompression schedule. Special consideration should be given to whether omitted decompression can be effectively completed underwater. Breathing surface interval oxygen and evacuation or recompression treatment on deck might be a better solution in some cases. Environmental conditions also play a huge role in the success of in-water decompression procedures.

Lost bottom divers

The following are various scenarios which can affect dive team composition:

- Separation during deployment
- Unable to reach the downline
- Unable to locate the ascent line
- Separation on dive site
- Swept off dive site
- Entanglement on bottom
- Buoy/Down-line breakaway

Procedures and equipment should be put in place to recall divers and/or abort the dive with an attempt to locate all in-water personnel. Divers should immediately establish visual surface markers by deploying a surface marker buoy (SMB) on a reel line to the surface. All divers must be accounted for immediately in this situation.

Rebreather challenges

- <u>Hypoxia</u>

Hypoxia is not a real concern for open-circuit divers, but can have profound effect on a closed-circuit rebreather diver. Hypoxia can lead to unconsciousness and death without warning. Malfunction of the oxygen injection system, or failing to turn on the oxygen supply valve is the major culprit in these situations. It is extremely important that the eCCR diver monitor their oxygen content in the breathing loop, verify that the unit's solenoid is firing properly and injecting oxygen, and check that there is an available oxygen supply gas leading to the breathing loop and that all gas supply valves are open. In the event of a hypoxic event, it is extremely important the diver reestablish normoxic levels as soon as possible or bailout to open-circuit scuba.

- Hyperoxia

  Divers should monitor themselves and their partners for signs of oxygen toxicity. A hyperoxic situation for an extended period can lead to oxygen-induced convulsions. This is an unpredictable event and can lead to drowning should the diver lose their mouthpiece. In the case of any oxygen toxicity symptoms, a diver should immediately flush the breathing loop with diluent, inform their dive partner of symptoms, and proceed to an ascent line and/or surface at the fastest rate consistent with the decompression model being employed. The affected diver should also immediately change setpoint to a lower FO_2 to reduce oxygen exposure. Immediate bailout to open-circuit scuba (bottom mix) is likely the best alternative to reaching a stable oxygen supply at the appropriate cutoff depth. When both divers are stabilized either on the ascent line or deco stop, a lift bag and slate should be sent to the surface, notifying the support team of the problem. A standby diver could be utilized in this situation and deployed to provide additional in-water support, monitoring this emergency and providing assistance as necessary. Further recommendations can be found in Mitchell et al. (2012).

- Hypercapnia

  Removal of exhaled carbon dioxide (CO_2) is an important function of the closed-circuit rebreather. Absorbent material made of a chemical agent helps to remove the byproduct of metabolism, accumulated CO_2 in the breathing loop. Canister size, depth of dive (gas density) and ambient temperature can affect eCCR absorbent performance. One must follow strict manufacturer guidelines and procedures when packing the CO_2 canister. Prolonged exposure to excessive CO_2 can lead to difficult breathing (dyspnea), headaches, nausea and progress to unconsciousness in the diver. Again, this can lead to drowning if the diver loses their mouthpiece. Bailout to open-circuit is once again the best alternative in a hypercapnia event.

- Loss of electronics

  Immediate bailout to open-circuit, begin planned contingency decompression using open-circuit decompression computer or back-up tables. Without electronics, the eCCR will not be able to provide an appropriate physiological gas mixture to the breathing loop.

- Flooding

  Immediate bailout to open-circuit, begin planned contingency decompression using open- circuit decompression computer or back-up tables.

- Loss of gasses

  If capacity is available, remain on loop and plug in additional offboard gas supply, abort dive and follow decompression schedule during ascent.

Mixed rebreather platform dive teams

Mixed rebreather platform use among diving teams can be a consideration, but this decision may lead to additional operational complexity, and/or require that special procedures be adopted to ensure divers are familiar with the performance and safety features of each eCCR unit on-site and in use.

Mixed open-circuit divers vs closed-circuit divers

This type of mixed team diving can be accomplished provided that divers are familiar with their individual equipment, emergency procedures are discussed and verified, and adequate out-of-air emergency and essential gas supply is available to either diver. In the case of decompression obligations and ascents, it is possible that there may be a mismatch in the times and depths required at each deco stop due to inert gas tissue on-loading controlling the decompression phases of the dive for each diver either in OC or CC mode.

Change in environmental conditions during the dive

Due to the dynamic nature of the open water environment and the prolonged exposure of divers conducting decompression dives, procedures and contingencies need to be developed for changes in environmental conditions. A plan for diver recall and/or aborted dive procedures should be in place and discussed with the dive team. Potential environmental changes that can have a direct effect on the bottom team members include, but are not limited to:

- Increase in current
- Increase in surface waves and/or swells
- Change in water temperature

Vessel of opportunity

There must always be a means of extracting an unconscious victim from the water in a timely manner. An oxygen delivery system capable of ventilating an unconscious victim should be readily available topside at the dive location. Shore diving may not require the use of a support vessel, if water extrication of a diver is readily available at the beach, lagoon or river bank. Use of a liveaboard vessel while conducting extended operational cruises is viable alternative for remote eCCR operations and can maximize the effectiveness of resources, personnel and collection of scientific data during a project (Sherman et al. 2010).

Emergency assistance planning

Plans to address an emergency should be well thought out, verified and put in place prior to commencing eCCR diving activities. There is the adage, *"An ounce of prevention is worth a pound of cure."* This is especially true in diving accident management. Emergency assistance planning (EAP) should include the following information and equipment:

- Personal medical information for all crew
- Medical treatment - standing orders from project management
- Nearest medical facility
- Medical response and contact information – EMS
- First aid procedure instructions
- Medical consultation – Third party or retained Diving Medical Officer contact
- Nearest recompression facilities and options for on-site treatment or evacuation
- *Life Flight* and/or Air, Sea & Rescue by military or Coast Guard personnel
- Communication equipment (satellite phone, cellular, VHF radio or private government band)
- Placement and storage of first aid kits, AEDs, oxygen delivery systems, stretchers, portable *Hyperlite*™ system and medications as required
- Incident reporting – organizational chain of command

Recompression therapy

Some diving programs might require having the ability to recompress a diver suffering from decompression illness (DCI) at the dive site. This is especially true if the dive profile involves in-water, staged decompression stops. Other operations may consider developing a response to treatment time guideline in their EAP (i.e., ≤30 min response) to an appropriate hyperbaric facility as an essential requirement. In either case, the use of a multi-place, mono-place or portable recompression chamber system in the field might be appropriate. If usable vessel deck space and/or programmatic expense is major limiting factor in providing a recompression chamber, then the use of the *Hyperlite*™, a portable hyperbaric stretcher is a viable alternative allowing appropriate hyperbaric emergency treatment readily available at the dive site. The ability to conduct on-site recompression therapy for decompression illness has in at least one case, provided a safe and effective therapeutic outcome for a stricken diver (Kesling et al. 2013). The author was involved in one case of reported DCI with an eCCR diver which he promptly treated in the field on a liveaboard dive vessel with a *Hyperlite*™ (Sherman et al. 2013). Complete resolution of symptoms was obtained by the patient following the prescribed treatment table.

Post-dive/Mission reporting

- Post-dive debrief – ALL HANDS
- Monitor dive team members for decompression-related symptoms post-dive
- Publications – Quick look report – Project summary

Lessons learned

Some problems identified in rebreather diving accidents are as follows:

- Failing to use a proper pre-dive checklist
- Not carrying an offboard bailout cylinder
- Solo diving
- Diver–Equipment interface (Diver/CCR unit familiarity)
- Failure in monitoring/disregarding onboard instrumentation/warning alarms
- Failure to monitor all gas supplies
- Ability to plug in offboard gas supply
- Unnecessary distractions during eCCR set-up and calibration
- Experience to recognize a problem requiring immediate bailout
- Decompression monitoring and back-up dive computer use/familiarization
- Strict eCCR set-up and ancillary equipment maintenance procedures
- Equipment assembly – i.e., essential O-rings, canister installation and sofnolime packing
- Depletion or reuse of oxygen cells, sofnolime and batteries

Summary

In summary, things to remember when launching a successful rebreather operation include the following techniques and procedures:

- Reliable checklist
- Team approach – planning and execution
- Well-maintained and practiced buddymanship skills
- Diving frequently on closed-circuit rebreather
- Equipment maintenance (regular intervals) with documentation/record keeping

- Maintaining adequate eCCR spares and supplies on-hand at all times
- Team approach for all offboard bailout gases and out-of-air scenarios
- Plug-in capability for offboard bailout gases to add to the breathing loop
- Practice, practice, practice

Acknowledgments

The author acknowledges the generous support from the NOAA Diving Program, AAUS, DAN and National Park Service for travel and logistics for attendance in this workshop.

References

AAUS Standards for Scientific Diving. 101 Bienville Blvd, Dauphin Island, AL 36528. May 2013 http://www.aaus.org/diving_standards

Kesling DE, Selby, J. The Efficacy using a *Hyperlite*™, Hyperbaric Stretcher for the Treatment of Serious Decompression Illness: A Case Report. In: Lang MA, Sayer MDJ, eds. Proceedings of the 2013 AAUS/ESDP Curaçao Joint International Scientific Diving Symposium. Dauphin Island, AL: AAUS; 2013; 147-56.

Mitchell SJ. Rebreather Forum 3 Consensus. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. AAUS/DAN/PADI: Durham, NC; 2014; 287-302.

Mitchell SJ, Bennett MH, Bird N, Doolette DJ, Hobbs GW, Kay E, Moon RE, Neuman TS, Vann RD, Walker R, Wyatt HA. Recommendations for rescue of a submerged unresponsive compressed-gas diver. Undersea Hyperb Med. 2012; 39(6); 1099-108.

Sherman C, Appeldoorn R, Carlo M, Nemeth M, Ruiz H, Bejarano I. Use of technical diving to study deep reef environments in Puerto Rico. In: Pollock NW, ed. Diving for Science 2009. Proceedings of the 28th American Academy of Underwater Sciences Symposium. Dauphin Island, AL: AAUS; 2010; 58-65.

Sherman C, Appeldoorn R, Ballantine D, Bejarano I, Carlo M, Kesling D, Nemeth M, Pagan F, Ruiz H, Schizas N, Weil E. Exploring the mesophotic zone: diving operations and scientific highlights of three research cruises across Puerto Rico and the US Virgin Islands. In: Lang MA, Sayer MDJ, eds. Proceedings of the 2013 AAUS/ESDP Curaçao Joint International Scientific Diving Symposium. Dauphin Island, AL: AAUS; 2013; 297-312.

QUESTIONS AND DISCUSSION

LIZ KINTZING: What is level 2 and level 3 training?

DOUG KESLING: It depends on who you are looking at in terms of the model. Some of the certifications that rolled out of here was a TDI model, ANDI model and IANTD model. Some focus on depths, some on dive numbers.

JEFF GODFREY: When you are diving with these teams where do you look at adding topside supervision? I have worked a lot with you in the past and on bigger projects they are always in place. When do you decide if topside supervision is necessary? How do you make that determination?

DOUG KESLING: That is a good question. In my world it was always the norm. It came with the territory. The decision might depend on risk analysis with some sort of matrix to see what kind of exposure risk, dependent on the nature of the diving. I would not apply it for all shallow water rebreather diving. But when you are doing some extensive decompression, you have it in place for every dive. It picks up a lot of different things, keeping the person focused and when there are distractions or shortcuts with diver setup or other equipment issues, effectively having someone clear and unencumbered by anything else to do can sort out immediate issues. And when you are doing vendor-based liveaboard diving, there can be a little bit of a communication error about how the vessel and how its crew is going to react to any given situation. I think it is imperative that you have a knowledgeable person there to run the ops and steer people in the right direction. So you see a different colored bag come up or a sample bag that is drifting away. The person involved in the operation has a lot more insight about what may be happening to the team, for example, why they have not seen the bag when the dive plan called for the bag to arrive at the surface in 25 min. They can start running through contingency plans, all depending on the dive operation.

JEFF GODFREY: Do you think it is determined less by team size and more by the depths that you are working at to consider it a requirement?

DOUG KESLING: It is hard to say.

JOHN HEINE: What is your estimate of the number of aborts you had in all the dives you did? Were there very many times when people could not get in and get their stuff done?

DOUG KESLING: No. There may have been one occasion in all of those dives conducted in Puerto Rico. Personal dive experience has a lot to do with it; a lot of the pre-dive planning; good vessel captain operations; good drops; good recoveries, those kind of things.

SIMON MITCHELL: Doug, the profiles you showed from the guy that got muscular decompression sickness, what settings was he using? What algorithm was he using that produced those deep stops?

DOUG KESLING: We used the 15/85 gradient factors on the AP Valve Silent Dive Vision at a 1.3 ATA PO_2. And then we ran a VR3 with 10% safety factor at a 1.25 ATA fixed PO_2. And we cleared both instruments with this Buhlmann-based model which approximately mirrored the Vision decompression schedule. And we would always clear both instruments to add conservancy to the deco schedule. The VR3 added another 10 min or so of deco at the 20 ft (6 m) stop.

SIMON MITCHELL: Do you have a sense of which one of those was prescribing the deep stops?

DOUG KESLING: If I recall correctly, I think it was the VR3s that were driving the deep stops. Seemed like the Vision would tend to push us up a little bit shallower a little bit faster. There are a couple other folks in the room that have done some live-aboard rebreather work as well.

STEVE SELLERS: I would like to go in a different direction. In developing your template, how much help did you have from your control board? Or was that all stuff that your team learned from other projects and applied? Where was your board in the overall or the overarching development of the protocols that they wanted you to use for this?

DOUG KESLING: We vetted things that were suggested to us. We relied on a lot of the different players in the scientific dive community that helped establish our operational guidelines because we were doing some things simultaneously regarding rebreather diving. And then for the UNCW purposes, we would have to submit our dive plan to them, because we have had some liability exposure and some risk. Rebreather diving was pretty much new to the University of Puerto Rico, so we went through a lot to develop a working model for their program. But we (UNCW) had limited experience in our diving control board with rebreathers. There were only a few people that had some exposure to them.

STEVE SELLERS: Was it more your experience leading the board or was it the board saying we want these questions answered?

DOUG KESLING: It was more my experience leading the board.

RICHARD PYLE: So on that list of problems/failures you gave, were those all causal factors in actual incidents or were those just observed breaches of protocol?

DOUG KESLING: Those were not in our particular project, but those were things I gleaned from looking at other programs to highlight some areas of concern. Overall, UPR was a very successful program and CCR progression. We did not have a lot of issues in the field. We had very good initial training and ran very tight protocols. People bought into that model and worked diligently. That laundry list I featured was really looking back and saying here are some pitfalls and here are some thing that can occur in the general sense of rebreathers, and why it is important to validate what we were doing because those things can occur.

DAVE PENCE: Couple of observations. One with regard to the extensive open-circuit technical training prior to moving into rebreathers. I think as we move forward, that is going to become more and more of a challenge because we are already seeing the vast advantages for using closed-circuit technologies for these extended range with their attendant complications. I think what we are going to see more and more is people wanting to move into rebreathers before they start working on the extended range. Early in the history of modern rebreathers, I think you saw that there were very experienced open-circuit technical divers who were getting into trouble by moving onto rebreathers too quickly and then trying to move deep too quickly. So I think it is kind of a balanced edge. My impression is that it is going to become harder and harder to require extensive open-circuit technical training before they move into range.

DOUG KESLING: I think your point is true. I never became a rebreather instructor, but I looked at this and I talked to Jeff Bozanic quite a bit - where we are going to have people who are going to start on a rebreather and never have open-circuit training, for one. So I think you have to really tailor programs and include components of what we were doing in open-circuit to the rebreather model so that those skillsets are developed along the way. Even the current rebreather training, if the end goal is the deep rebreather work, you are not getting the essential skillsets to do that. So in that progression, that 1, 2, 3 tier, those things, from my experience in the open-circuit world, really have to be emphasized.

DAVE PENCE: My observation is out of the 20 or so technical rebreather divers that we have produced at UH, probably the first four or five had extensive open-circuit technical, and that was simply because we did not have the rebreathers before we started that. My second observation is that our experience and culture in Hawaii has been very different in terms of topside supervision. One of our philosophies is that we want the most qualified person in the position to respond. And so we have typically used a topside support diver who is versed in basic response, what to do in specific emergency protocols like a certain signal marker comes up. But really we would prefer to have the person who is making the decisions to be fully invested in the dive. So that being said, you are absolutely right; there needs to be someone who is not absolutely invested in the science on site helping cry foul if people are starting to push the science instead of the operational security.

DOUG KESLING: One other comment I will make related to Dave's comment is that the team in Puerto Rico really wanted to fast track their progression. They wanted to get out there to the coral work and dive. They did not realize when they wrote the proposal about the time commitments and the training evolution that was at stake. I had to reel them in a little bit. They had a great opportunity, because they had access to deep water, they could go out on and dive on a regular basis. So in my every two-trip-per-year monitoring, they realized in short order that this was going to take some time to develop the skillset and do it and become effective, which led to our three successful CCR cruises. But it just did not happen overnight, and that was one of the things that was relevant and came out of the CCR progression. So in a proposal, you have to allow time for skills to develop. But we had good, strong, divers with a lot of good diving backgrounds; that was key. Adding the open-circuit, technical dive training, which ran them through the paces, was also key to their rebreather development early on.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

Emergency Procedures and Managing a Rebreather Whilst Task Loaded: The Implementation of Rebreather Technology into Scientific Diving Projects

Phillip A. Short

Springfield, Bath Road, Devizes, Wiltshire, SN10 1PH, United Kingdom
phil@philshorttechnical.co.uk

Abstract

The purpose of this manuscript is to initiate a discussion into the complications of using rebreather technology in a work diving theater. The working diver in question is a scientist or scientific support person who is required to perform a task as their prime objective whilst also maintaining life support equipment functionality.

Keywords: pre-dive checks, prebreathe, psychology, open-circuit, closed-circuit, head up display, hypoxia, hyperoxia, hypercapnia

Introduction

The prime objective of a scientific diver is to perform their research or science. In a safe dry land environment this may well be the only task to hand. As a scientist working in an underwater environment the task of life support takes priority over all other tasks, although once deeply focused in research or recording of scientific data this may not be the case with potentially fatal results. With open-circuit scuba equipment training is simple and well developed, equipment is reliable and uniformly tested to international standards and in water requires little operation other than the monitoring of available gas supply. With the advent of rebreather technologies be it passive, active or electronic semi-closed, mechanical or electronic fully-closed, we enter a different and far more complex operational procedure as the gas breathed from the system is dynamic making constant monitoring and, in some cases, control of the equipment imperative.

The aim of this manuscript is to look at potential operating procedures to allow the use of such rebreather equipment whilst both achieving the scientific objectives and maintaining the safety of a diving operation.

Methods

The first question to ask of the scientist is "Are they a scientist or a diver?" The likely answer to which will be, "both" although the true answer is more likely to be that they are a scientist who has some degree of diver training and or experience to enable them to continue to be that scientist whilst underwater.

Pre-dive checks and an appropriate prebreathe are critical to boosting rebreather dive safety, much like preflight checks on an aircraft. These pre-dive procedures should include a number of elements.

Pre-assembly checks

Pack and fit or fit a pre-packed absorbent canister into the rebreather following the manufacturer's guidelines from manufacturer approved training and from the rebreather user manual. Canister packing varies from canister type to type and from manufacturer to manufacturer. Procedure for the unit being used should be learnt, practiced and followed without exception. If a part used canister is to be re-used it should be within the manufacturers guidelines for such re-use and the canisters used time and remaining time should be noted and calculated.

The author has worked as Diving Safety Officer (DSO) on projects following a policy of discarding partly used carbon dioxide absorbent at the end of each diving day regardless of remaining time on said absorbent. This procedure has negligible cost implications when compared to the potential safety increase from the relatively unknown effects of leaving partly used canisters for an extended period of time and reusing them.

<u>Analyze both onboard cylinders</u> (oxygen and diluents) and all offboard cylinders with an oxygen or oxygen and helium analyzer as appropriate and label each cylinder individually with as a minimum the mix and the maximum operating depth (MOD) based on the maximum partial pressure of oxygen (PO_2) approved by the diver's institution and/or Diving Safety Officer.

<u>Complete a mushroom (one-way) valve test</u> to ensure that flow around the rebreather is in the correct direction and that flow in the reverse direction is not possible. By way of example this check for a rebreather that exhales to the diver's right is completed in the following manner: place the rebreather mouthpiece (dive surface valve [DSV] or bailout valve [BOV] assembly) in the closed-circuit position, place in the mouth and breathe normally. Block (With the flat of the hand) the exhale (right hand) side and gently exhale. Exhalation should NOT be possible. Remove the hand from the exhale (right hand) side and block (with the flat of the hand) the inhale (left hand) side and gently inhale. Inhalation should not be possible.

The importance of this simple check cannot be overemphasized as without it a failed or damaged mushroom valve could enable gas to be breathed back and forth rather than around the rebreather. This would enable the exhaled gas to be rebreathed rather than it passing through the absorbent canister that would quickly lead to hypercapnia.

A full set of pre-dive checks

The pre-dive checks are designed by the manufacturer of the specific rebreather in most cases and may be in the form of a tick, complete and sign off pre-dive check sheet or electronic as part of the rebreathers display system. The electronic version can be passive, that is, a series of screens describing a check with a button push allowing the diver to confirm the check complete to move on to the next check. The weakness of this is that screens can be confirmed with the button push even if the check has not been completed. Active screens include various checks that interact with the rebreather sensors to confirm a check has been made. For example, use of an internal pressure transducer to monitor internal pressure to confirm that a negative (vacuum) test has been completed and held for a required time span. Active screens cannot be passed until the test is passed.

In addition, most of the main diver training agencies print a generic pre-dive rebreather check card or slate to be used in conjunction with the manufacturer's pre-dive sequence. In addition, many institutions author their own dive operation risk assessments including, but not limited to, pre-dive equipment checks.

The author believes that safety could be increased if an agreed universal pre-dive check sheet for rebreather use in scientific diving operations were independently produced and used by all institutions and an appendix were created for each rebreather (platform) in use and approved or co-authored with the manufacturer of that specific rebreather.

An appropriate prebreathe

In recent times much controversy has arisen over rebreather prebreathes, should they be completed at all, if so for how long and in what matter and most importantly why do a prebreathe and what does it achieve?

An extended prebreathe of 1-5 min does not 'activate' the absorbent material, the first exhaled breath entering the canister and making contact with the absorbent material will start the exothermic reaction of carbon dioxide being absorbed. A widely accepted prebreathe duration is between 3-5 min, this duration however will not necessarily produce symptoms of carbon dioxide breakthrough that a diver would recognize, the extended duration of the dive time along with other factors such as workload, water temperature and depth could however cause hypercapnia during the dive.

So, what can a prebreathe tell us? It can confirm that the electronic system of an electronic closed-circuit rebreather (eCCR) or an electronic semiclosed-circuit rebreather (eSCR) is functional or that the gas addition system of a passive or active SCR is functional. It can confirm that a desired 'setpoint' can be maintained and that the oxygen cylinder is turned on. On some units it can confirm the activation and progress of a thermal wave through the absorbent material via a thermal monitoring system within the canister or better still on some units it can confirm no carbon dioxide on the inhale side of the loop via a CO_2 monitor.

In short the prebreathe in effect re checks many of the steps of pre-assembly and pre-dive checks live on a fully assembled activated rebreather just prior to a dive and as such should be considered as mandatory.

The author, on projects he has worked as DSO, has required and enforced a policy of a five minute prebreathe with the nose blocked to prevent involuntary nasal venting to deal with symptoms of hypercapnia whilst watching the primary and secondary displays of the unit to confirm that oxygen injection is occurring and that a desired setpoint can be maintained. All of these reasons are positive benefits to a prebreathe and there are no negatives to this simple pre-dive drill.

The author believes that safety could be increased if the scientific institutions, their DSO's and their platform manufacturers could agree on a prebreathe procedure and duration and enforce it uniformly.

Do not get lazy, take short cuts, 'reinvent the wheel' or skip this basic life support! Pre-dive checks have prevented accidents and incomplete or absent pre-dive checks have contributed to fatalities!

The psychology of pre-dive checks

The concern here is there will always be people who for one reason or another believe they are above the system!

We can separate divers who use rebreathers into three simple categories:

1. Those who will always use checklists.
   This is common in the military use of rebreathers where a standard operating procedure (SOP) has been established and post-training is followed without question.

2. Those who will use a checklist if they believe it will add value to their actions.
   This could be said to be common in the scientific diving community as a scientist has an enquiring mind and will look deeply into each step of an SOP and determine if it has value before accepting that it should be completed.

3. Those who never use checklists.
   This is common in some areas of recreational or sport diving especially using open-circuit equipment, but also in rebreather use, where after a large number of 'event-free' dives the individual feels checks are no longer needed.

Simplicity of pre-dive checks

One solution to encouraging divers to complete pre-dive checks is to make them simple and user-friendly. Early in the evolution of educational system design within the technical portion of the recreational diving community a suggested simple pre-dive sequence followed an acronym similar to commonly used buddy checks. This is represented below:

F - Flow - Ambient and intermediate pressure.
L - Loop - Positive and negative loop integrity.
A - Analyze - Oxygen/Diluent/Bailout.
G - Gas - High pressure contents and leak check.
S - Stack and System - Prebreathe monitoring setpoint maintenance.

The steps of FLAGS may not always be completed in sequence but can be checked off as done and if the 'sign off sheet' or on screen electronic pre-dive check steps of most commonly available rebreathers are scrutinized each check can easily be categorized under one of the five steps of FLAGS.

Risk! What are you breathing?

"Do you really know what you are breathing?" is a very good question to ask yourself whilst breathing from a rebreather! With open-circuit diving equipment, provided that the gas is analyzed and labeled pre-dive and then used within its operational range, what you are breathing is a constant, unchanging gas. Whilst with rebreather because one or more gases are added to a breathing loop that is being recycled and rebreathed the gas can be said to be 'dynamic'. This means that unlike open-circuit where hypoxia and hyperoxia can be prevented by using the right gas at the right depth with rebreather the gas within the loop can change during the dive if for example too much oxygen is injected (for example, if a solenoid fails in the open position) or oxygen stops injecting (for example, due to an empty onboard oxygen cylinder).

The key difference is that with open-circuit if the equipment fails it is immediately apparent through either a free flow or the inability to breathe whereas with rebreather the diver may be able to continue ventilating normally but whilst breathing a gas that is hypoxic or hyperoxic with little or no warning.

Instrumentation

All diving equipment has instrumentation to ensure diver safety, whether that be instrumentation controlled and monitored by a surface supervisor as in umbilical hard hat operations, a simple submersible pressure gauge as in open-circuit scuba or the various life support information displayed <u>on a rebreather.</u>

The first electronic, closed-circuit rebreathers had a simple handset that only displayed the three PO_2 readings from the three independent oxygen cells. These handsets were often mounted via clips to the divers harness or wrist mounted and the diver had to lift them into the field of view to monitor PO_2. Once task loaded it is simple to become carried away with the job at hand and forget to do this, a situation that has caused fatalities! Modern rebreather research and development has striven to reduce this risk to a minimum by optimizing displays with evolving technologies.

Head up display (HUD)

The head up display is one of the most significant contributions to safe rebreather diving to date! It enables the diver to look through a display at their dive objective, that is, to pay full attention to the grid laying and survey of an archeological site whilst always having at minimum a Green/Red Go/No Go light in the field of vision. This effectively allows near-constant monitoring of PO_2.

The HUD can be a simple 'green equals good keep breathing' or 'red equals immediately bailout to open-circuit,' such as is found in the Hollis Explorer eSCR. They can also provide a more informative analysis of the PO_2 of each sensor via a color/flash sequence code, such as with the Sub Gravity Hammerhead CCR. A more informative multi-function HUD can display PO_2, decompression status and alarms, for example with the VMS Sentinel CCR. Finally, a HUD can provide complete dive computer information, such as with the Shearwater near-eye remote display (NERD).

The HUD can also be mimicked or replicated on the rear of the rebreather for the benefit of the buddy, supervisor or other dive team members. This feature is available with the Ouroboros, Sentinel, MK VI/VII Poseidon, and Explorer systems.

Primary

The primary display is usually wrist mounted and shows all information relating to the dive and the rebreather system. Information typically includes PO_2 reading from the three sensors that are being followed to control the desired setpoint, depth, dive time, the current no decompression limit or the decompression ceiling, estimated time to surface, and any system status alarms. The primary is also where the controls of the rebreather can be accessed by button pushing sequences, allowing changes in diluent, PO_2 setpoint, and bailout status, among others.

Secondary

The secondary display is usually either clipped to the diver's harness or wrist mounted on the opposite wrist to the primary display. The secondary will often show output from the three sensors as independent from the primary, along with depth, time, and decompression information based on either their own sensor readings or a fixed setpoint.

Risks Associated with Rebreather Diving

Hypoxia

A low level of oxygen at a cellular level could be described as the most serious risk to the rebreather diver. *The author has personally lost two very experienced and diligent CCR rebreather diver friends to hypoxia.* Symptoms may be vague and of a sufficiently low physical stress level to go unnoticed by a task loaded diver. Warning symptoms may also be masked by others promoting mild euphoria or a feeling of wellbeing. For this reason an in depth analysis of cause and prevention of this issue follows.

Question. Why did the rebreather reach a hypoxic PO_2?

The dropping of PO_2 in a rebreather loop that was previously at the correct PO_2 takes time if remaining at a constant depth. For example, if the gas supply to the rebreather (oxygen in a closed-circuit or possibly nitrox in a semiclosed-circuit system) is exhausted or cannot be added to the rebreather anymore due to mechanical or electronic system malfunction then the PO_2 within the breathing loop will drop at a rate proportional to the divers metabolism. If the diver is ascending the remaining loop gas PO_2 will drop even faster in accordance with Dalton's law.

An example can be provided for a Sentinel electronic CCR at 20 msw (66 fsw) depth with an onboard diluent of air (21% oxygen) and a PO_2 setpoint of 1.2 ATA. For this discussion it will be assumed that the ADV flow stop was closed to disable the delivery of diluent. In this case as the diver consumes oxygen metabolically the loop volume will drop proportionally. Soon after the diver will experience a restriction during inhalation that should alert them to a problem. This situation could develop whilst the diver remains at a fixed depth, for example, while on the bottom when possibly very task loaded with science objectives. If the ADV was functioning, the loop volume decrease would activate the valve to add diluent. If the correct diluent was selected for the dive plan, ADV activation would raise the PO_2 above the level of hypoxia risk. For the example here the 21% diluent at 20 msw (66 fsw) would provide a PO_2 of 0.63 ATA.

For our example the flow stop on the feed line to the oxygen solenoid was closed and a stopwatch timer was started. For the next two solenoid fires initiated by the electronics the remaining volume of oxygen in the lines beyond the flow stop was injected. Subsequent solenoid fires would add no more oxygen. Approximately three minutes after starting the exercise the HUD would go from a solid green to a slow flashing green, indicating a low PO_2 (less than 1.09 ATA in this example), After approximately five minutes a slow flashing blue/green HUD minor alarm was triggered immediately after the diver noted that on inhale the rebreather counterlung was 'bottoming out' at the end of a normal inhale), this point corresponding to a PO_2 of approximately 0.9 ATA.

If the diver was diligently monitoring his or her rebreather instrumentation the slow drop in loop PO_2 would be seen long before hypoxic levels were reached. Appropriate training and diligent execution will dramatically reduce the likelihood of serious issues developing. A HUD system can facilitate high frequency monitoring.

Hyperoxia

The condition of high level of oxygen at a cellular level is associated with a risk of central nervous system oxygen toxicity. Manifestation can include convulsions, creating a high risk for drowning.

Question. Why did the rebreather reach a hyperoxic PO_2?

The most common and likely reason for a CCR loop reaching an elevated PO_2 beyond setpoint is a mechanical failure of either the electronic or the manual gas injection paths. In other words, with a solenoid failing in the open position or the manual injector system o-rings failing.

Rising PO_2 would be indicated by displays and alarm systems. The diver could also notice an increase in positive buoyancy and a feeling of fullness in the counterlungs during exhalation. Practically, hyperoxia would likely not develop instantaneous and should not go unnoticed, particularly if the diver were using a rebreather fitted with a HUD.

Hypercapnia

Condition of excessive carbon dioxide concentration at a cellular level. Hypercapnia can develop with open- or closed-circuit equipment due to faulty equipment or overworking, but the risk with closed-circuit is greater with the possibility of failure of the scrubber canister to remove CO_2 (breakthrough) which leads to the diver rebreathing their exhaled carbon dioxide.

Symptoms of hypercapnia include elevated breathing rates, shortness of breath and headaches. It is very possible that a CO_2 event underwater could lead to unconsciousness and drowning with little or no warning.

The plan should therefore always be prevention rather than response or cure.

Carry bailout, use bailout and once bailed out stay bailed out!

Carbon dioxide monitoring

CO_2 monitoring technology is well established, and while integrating it within the wet, warm environment of a rebreather is complex, it has been implemented by various manufacturers in recent years, including VMS (Sentinel), Hollis (Explorer) and AP (Vision Inspiration/Evolution). Effective CO_2 monitoring can overcome a huge hazard, especially when integrated with a HUD.

The current standard is infrared (IR) sensor technology, which is prone to errors from moisture within the rebreather environment. The IR sensors frequently confuse water droplets as CO_2, making the use of various water trap barriers critical for proper function.

It is critical for divers to carry the appropriate bailout gas to handle system failures. Bailout planning is mandatory for all dives and must include taking into consideration the elevated breathing rate associated with stress.

Decompression

The issue with absorption of inert gas into and the release of gas out of the tissues during an exposure to depth exists for open, semiclosed and closed-circuit diving. Dives must be planned, including bailout supplies and volumes appropriate for both surfacing and to meet the increased decompression obligation that may arise from bailing out.

Integration of basic decompression data into a HUD can reduce task loading during ascent. A simple system warning of decompression required, arrival at ceiling and violation of ceiling can easily be incorporated into the HUD with a LED flash sequence such as the White LED on the VMS Sentinel.

Task loading

Is multi-platform familiarity possible? Open-circuit regulators and BCDs are typically very similar across the range of manufacturers and product, so cross training is generally not required to move from product to product. This is not the case for rebreather technologies, where there are nearly as many different types of DSV, BOV, HUD signals and sequence and manual inject options, as there are rebreathers.

Modern electronically-controlled CCR offer many different control systems. It may not be realistic to expect that a diver can attain reflex familiarity with multiple different electronics to maintain sufficient competency to allow platform switching on a semi-regular basis.

The author has taught on CCR full time professionally for the last 10 years and logged 3000+ hours within that time frame on rebreather. Although the author teaches several platforms his choice of platforms has been limited to two main electronic control systems, the VR system controlling Ouroboros, Sentinel and Explorer and the Shearwater system controlling Hammerhead CCR and PRISM 2 CCR. With an average of 300 hours per year in water time has permitted enough training and practice dives to maintain currency on both control systems. The author has chosen not to expand beyond these two systems based on the reasons above.

Possible Solutions to Risks Associated with Rebreather Use

Safety net philosophy

The idea here is that a task-loaded diver especially one 'at work' such as a scientist could elect to run the required loop PO_2 (e.g., 1.00 ATA) on a CCR manually through periodic injection via the manual addition button and monitoring of the HUD or primary whilst running the electronic control system at a lower 'safety net' value (e.g., 0.70 ATA). A well-trained, experienced and current rebreather diver would accomplish this by use of the 'minimum loop volume' skill. The SOP would require the diver to then monitor time and check their primary and secondary displays against each other at minimum once every five minutes to ensure target PO_2 was being maintained.

Guardian angels

The principal task of the scientific diver is to conduct their science; the dive is merely a means to access the work site for that science. The principal task of the onsite DSO is to ensure the safety of the dive team. The more complex the dive and the more complex the scientific work the greater the risk. The deployment of Scientist Sentinels to work through pre-dive with (not for) the scientist and then dive with them with the primary function of monitoring their condition, actions and rebreather instrumentation is recommended. For example, the support diver could act to investigate a rear HUD alarm that the scientist does not respond to. The support diver could also reduce task loading of the researcher by carrying some science equipment (not personal life support or primary bailout).

The author has worked with Woods Hole Oceanographic Institution over the last four years on an archeological project in Crete and Antikythera Greece using this 'Guardian Angel' approach. Each scientist or pair of scientists are accompanied through the whole pre-dive, dive and post-dive procedure. This involved electronic closed-circuit rebreather use for mapping, survey and recovery in up to 60 msw [200 fsw])

Equipment optimization

It is important not to lose track of the objective in a dive and in the case of an institutional scientific dive that objective is the science, second only to diver safety. With that in mind a rebreather may not always be the right tool for the job. In some cases the task could be achieved more effectively and/or more safely on another equipment platform. Rebreathers are simply one tool in a varied toolbox of options to conduct scientific research underwater, from simple open-circuit air to one-atmosphere Exosuit or mini submersibles.

Discussion

The discussion resulting from the presentation that prompted this paper and the manuscript should initiate with the following key topics:

Should minimum dive and dive hour numbers to maintain dive status within an institution be reviewed?

Should scientific institutions and or their Dive Safety Officers permit rebreather modification outside of manufacturer specification?

Should the institutions represented at the conference form a working group to construct and author a generic pre-dive check for rebreathers?

Should institutions work with manufacturers to construct specific appendix pre-dive checks to complement the above generic pre-dive check suggestion?

Acknowledgments

The authors acknowledge the professional support of Sub Gravity (Manufacturer of the Hammerhead CCR), VMS (Manufacturer of the Sentinel CCR) Shearwater (Manufacturer of the NERD HUD) and Dr. Simon Mitchell.

QUESTIONS AND DISCUSSION

SIMON MITCHELL: Your discussion of preventing hypercapnia through attention to detail with the CO_2 scrubber was absolutely on the money. I want to remind everybody that the most common cause of hypercapnia in diving is CO_2 retention. I would add into that things like realistic expectations of ability to work underwater especially when deep and gas density calculations in planning your dives to try and mitigate the risk of CO_2 retention, as well as those things you alluded to in relation to the CO_2 canister.

JOHN BRIGHT: You mentioned on optimizing equipment that you should select the right tool for the job based on what your anticipated task loading is and the complexity of the life support system. I think in a separate point you also mentioned support for Park Service policy of doing like a blanket adoption of a system to build proficiency. How would you recommend balancing these elements?

PHIL SHORT: I do not know how all of your organizations work because you have different team members trained for different things. But if you are called in to do a job in 30 ft (9 m) of water, stick the team on that job that are trained on equipment most appropriate for that job. And if you get called into a job at 200 ft (60 m), put the rebreather team on that, which enables you to manage both those scenarios. You are right, those two things seem to be in contradiction. I think the more important of those two points, if you are going to push one of them, is the single platform familiarity to stay CCR proficient. The rebreather might not be the right tool for a 30 ft (6 m) project, but it can do that job. Whereas, not having the ability to use the rebreather with motor reflex while on a 200 ft (60 m) job is far more of a safety issue than the other one.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

The Value of Closed-Circuit Rebreathers for Biological Research

Richard L. Pyle[1], Phillip S. Lobel[2], Joseph A. Tomoleoni[3]

1. Ichthyology, Bishop Museum, 1525 Bernice Street, Honolulu, HI 96744, USA
deepreef@bishopmuseum.org
2. Department of Biology, Boston University, 5 Cummington Mall, Boston, MA 02215, USA
3. US Geological Survey, Western Ecological Research Center, Santa Cruz Field Station,
100 Shaffer Rd, COH Bldg., Santa Cruz, CA 95060, USA

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.

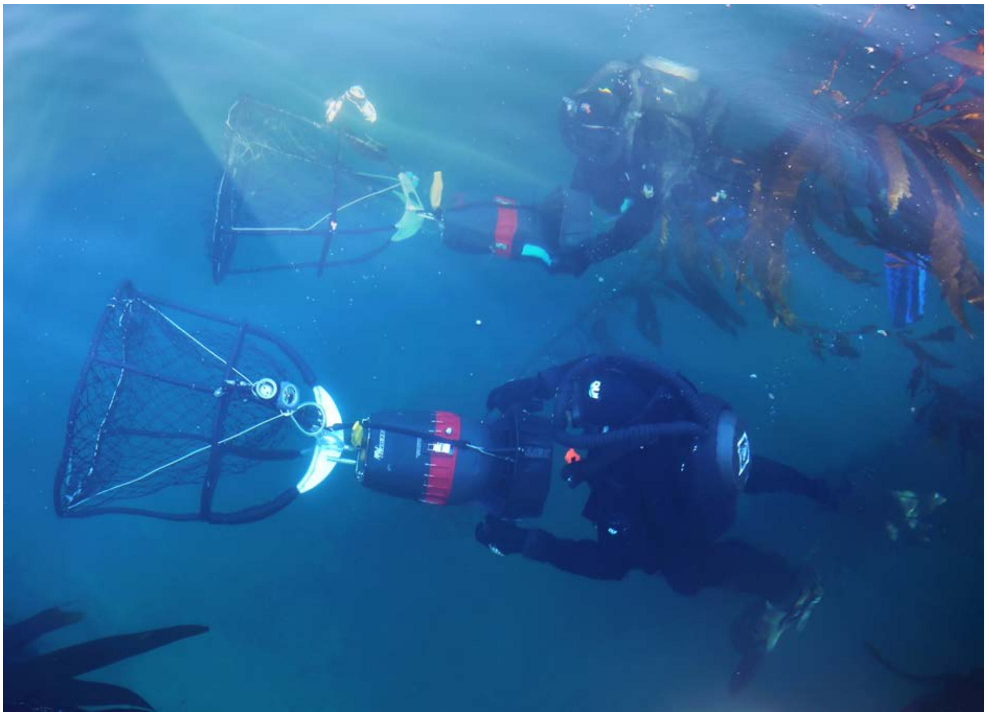


Figure 3: A USGS sea otter capture dive team, using Carleton COBRA oxygen rebreathers, begins a capture dive. Photo: David Osorio, CDFW.

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]).

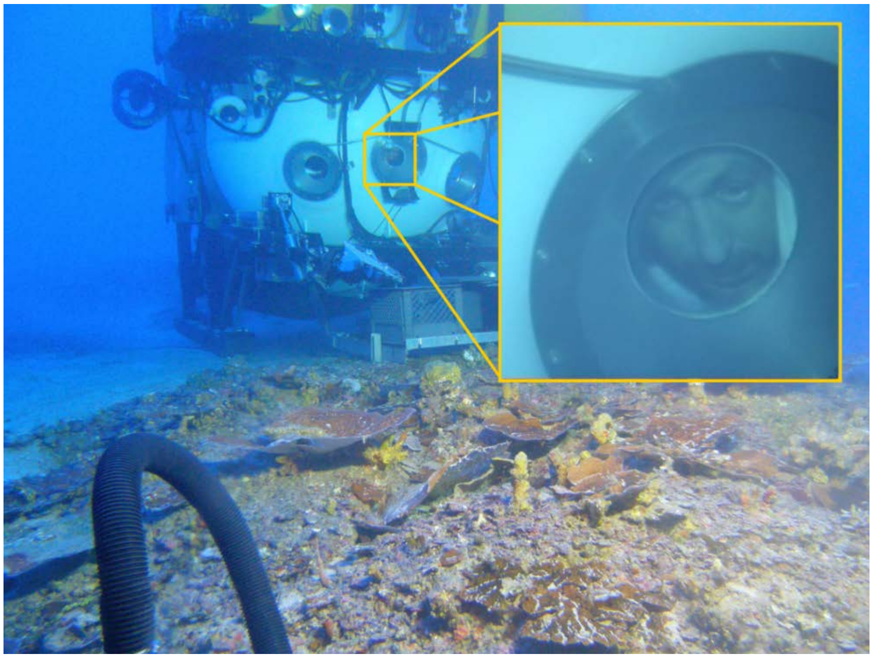


Figure 6. Deep-sea submersibles isolate the researcher from the study environment. Photo: Hawaii Undersea Research Laboratory.

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).

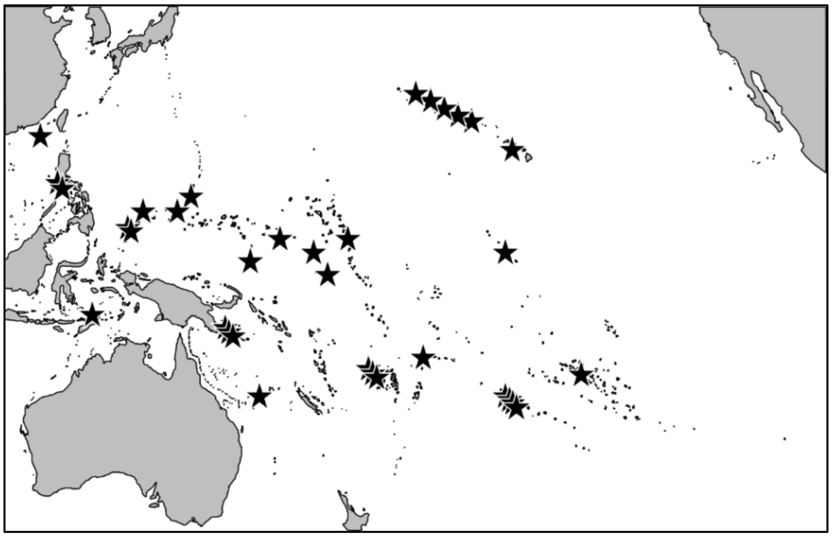


Figure 8. Map of locations where remote field operations involving closed-circuit rebreathers have been conducted by R.L. Pyle and colleagues.

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.

Acknowledgments

We thank Randall Kosaki, Greg McFall, David Pence, Heather Spalding, and Jeffrey Bozanic for their insights on using rebreathers for biological research, and for use of images. P. Lobel's rebreather research was supported by the Army Research Office (DAAAG55-98-1-0304, DAAD19-02-1-0218), Office of Naval research (N00014-19-J1519, N00014-92-J-1969 and N00014-95-1-1324) and Legacy Resource Management Program (DACA87-00-H-0021, DACA87-01-H-0012, DAMD17-93-J-3052, W912DY-06-2-0017). Use of trade, product, or firm names does not imply endorsement by the US Government.

References

Bodkin JL, Monson DH, Esslinger GG. Activity budgets derived from time-depth recorders in a diving mammal. J Wildlife Manage. 2007; 71: 2034-44.

Bodkin JL, Esslinger GG, Monson DH. Foraging depths of sea otters and implications to coastal marine communities. Marine Mammal Sci. 2004; 20: 305-21.

Bright TJ. Bioacoustic studies of reef organisms. Natural History Museum Los Angeles County Science Bulletin. 1972; 14: 45-70.

Chen B. Crown of Thorns starfish removal program on track. Samoa News. 2014; 23 April edition.

Cole RG, Syms C, Davey NK, Gust N, Notman P, Stewart R, Radford CA, Carbines G, Carr MH, Jeffs AG. Does breathing apparatus affect fish counts and observations? A comparison at three New Zealand fished and protected areas. Mar. Biol. 2007; 150: 1379-95.

Collette BB. Results of the Tektite Program: ecology of coral-reef fishes. In: Lang MA, Baldwin CC, eds. Methods and Techniques of Underwater Research. Proceedings of the American Academy of Underwater Sciences Scientific Diving Symposium. Washington, DC: Smithsonian Institution; 1996:83-7.

Collette B., Earle SA (eds). Results of the Tektite Project: ecology of coral reef fishes. Sci Bull Nat Hist Mus LA County. 1972; 14: 1-180.

Davis RH. Deep Diving and Submarine Operations (6th ed). Tolworth, Surbiton, Surrey: Siebe Gorman & Company Ltd.; 1955; 693 pp.

Dickens LC, Goatley CHR, Tanner JK, Bellwood DR. Quantifying relative diver effects in underwater visual censuses. PLoS ONE. 2011; 6:e18965.

Fay RR, Popper AN. Hearing in fishes and amphibians: An introduction. Ch. 1, In: Fay RR, Popper AN (eds). Comparative Hearing: Fish and Amphibians, Springer-Verlag, New York, 1999; pp. 43-100.

Fock A. Analysis of recreational closed-circuit rebreather deaths 1998–2010. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 119-27.

Hall H. The sound of silence. Ocean Realm. 1990; Fall: 12-3.

Hamilton RW. Technology inspired: The closed-circuit rebreather. aquaCorps. 1990; 2: 10-14.

Hanlon RT, Hixon RF, Hendrix JP Jr., Forsythe JW, Sutton TE, Cross MR, Dawson R, Booth L. The application of closed circuit scuba for biological observations. In: Blanchard J, Mair J, Morrison, I, eds. Proceedings of the Sixth International Scientific Symposium of CMAS, Proceedings of the Diving Science Symposium. London: National Environmental Research Council; 1982: 43-52.

Harris R. Rebreathers: overcoming obstacles in exploration. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 56-61.

Hinderstein LM, Marr JCA, Martinez FA, Dowgiallo MJ, Puglise KA, Pyle RL, Zawada DG, Appeldoorn R. Theme section on "Mesophotic Coral Ecosystems: Characterization, Ecology, and Management". Coral Reefs. 2010; 29: 247–51.

Lindfield SJ, Harvey ES, McIlwain JL, Halford AR. Silent fish surveys: bubble-free diving highlights inaccuracies associated with scuba-based surveys in heavily fished areas. Methods Ecol Evol. 2014; 5(10): 1061-9.

Lobel PS. Diel, lunar and seasonal periodicity in the reproductive behavior of the pomacanthid fish, *Centropyge potteri* and some other reef fishes in Hawaii. Pac Sci. 1978; 32: 193-207.

Lobel PS. Fish bioacoustics and behavior: passive acoustic detection and the application of a closed-circuit rebreather for field study. Mar Tech Soc J. 2001; 35: 19-28.

Lobel PS. Synchronized underwater audio-video recording. Listening to Fish: Proceedings of the International Workshop on the Applications of Passive Acoustics to Fisheries. Cambridge, MA: MIT SeaGrant publication; 2003: 127-30.

Lobel PS. Scuba bubble noise and fish behavior: a rationale for silent diving technology. In: Godfrey JM, Shumway SE, eds. Proceedings of the American Academy of Underwater Sciences 24th Annual Symposium Groton, CN: University of Connecticut; 2005: 49-59.

Lobel PS. Underwater Acoustic Ecology: Boat Noises and Fish Behavior. In: Pollock NW, ed. Diving for Science 2009. Proceedings of the American Academy of Underwater Sciences 28th Symposium. Dauphin Island, AL: AAUS; 2009: 31-42

McDonald CM, Lang MA. Rebreather perspective: The scientific-diving community. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 35-43.

Pence DF, Pyle RL. University of Hawaii dive team completes Fiji deep reef fish surveys using mixed-gas rebreathers. SLATE. 2002; April: 1-3.

Parrish F, Pyle RL. Surface Logistics and Consumables for Open-Circuit and Closed-Circuit Deep Mixed-Gas Diving Operations. Proceedings of the MTS/IEEE Oceans 2001 Conference. 2001; (3): 1735-7.

Parrish FA, Pyle RL. Field comparison of open-circuit scuba to closed-circuit rebreathers for deep mixed-gas diving operations. Mar Tech Soc J. 2002; 36(2): 13-22.

Popper AN, Fay RR. The auditory periphery in fishes. Ch. 3, In: Fay RR, Popper AN (eds). Comparative Hearing: Fish and Amphibians, Springer-Verlag, New York, 1999; pp. 43-100.

Pyle RL. Section 7.9. Multiple gas mixture diving, Tri-mix. In: Flemming NC, Max MD, eds. Scientific Diving: a general code of practice, Second Edition. Paris: United Nations Educational, Scientific and Cultural Organization (UNESCO), and Scientific Committee of the World Underwater Federation (CMAS); 1996: 77-80.

Pyle RL. Chapter 7. Use of advanced mixed-gas diving technology to explore the coral reef "Twilight Zone". In: Tanacredi JT, Loret, J. eds. Ocean Pulse: A Critical Diagnosis. New York: Plenum Press; 1998: 71-88.

Pyle RL. 1999. Mixed-Gas, Closed-Circuit Rebreather Use for Identification of New Reef Fish Species from 200-500 fsw. In: Hamilton RW, Pence DF, Kesling DE, eds. Assessment and Feasibility of Technical Diving Operations for Scientific Exploration. Nahant, MA: American Academy of Underwater Sciences. 1999: 53-65.

Pyle RL. Assessing Undiscovered Fish Biodiversity on Deep Coral Reefs Using Advanced Self-Contained Diving Technology. Mar Tech Soc J. 2000; 34(4): 82-91.

Pyle RL. Rebreather evolution in the foreseeable future. In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Wrigley Marine Science Center, Catalina Island, CA; 2016; 40-64.

Quick D. A History of Closed-Circuit Oxygen Underwater Breathing Apparatus. Royal Australian Navy, School of Underwater Medicine; 1970, RANSUM-1-70.

Rowley SJ. Refugia in the 'twilight zone': discoveries from the Philippines. Marine Biologist. 2014; 2: 16-7.

Sanders GS, Wendell FE. Closed-circuit Oxygen Apparatus: Minimizing Risks and Improved Efficiency. Proceedings of the American Academy of Underwater Sciences Eleventh Annual Scientific Diving Symposium, Honolulu, Hawaii. 1991: 87-101.

Schmidt MB, Gassner H. Influence of scuba divers on the avoidance reaction of a dense vendace (*Coregonus albula* L.) population monitored by hydroacoustics. Fish Res. 2006; 82: 131-9.

Sellers SH. Overview of rebreathers in scientific diving 1998-2013. In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Wrigley Marine Science Center, Catalina Island, CA; 2016; 5-39.

Seymore B. US National Park Service perspective. In: Lang MA, Steller DL. Proceedings of the AAUS Rebreather Colloquium. Monterey, CA: American Academy of Underwater Sciences. 2012: 17-8.

Sharpe FA, Dill LM. The behavior of Pacific herring schools in response to artificial humpback whale bubbles. Can J Zool. 1997; 75: 725-30.

Sherman C, Appeldoorn R, Carlo M, Nemeth M, Ruíz H, Bejarano I. Use of technical diving to study deep reef environments in Puerto Rico. In: Pollock NW, ed. Diving for Science 2009. Proceedings of the American Academy of Underwater Sciences 28th Symposium. Dauphin Island, AL: AAUS; 2009: 58-65.

Sieber A, Pyle R. A review of the use of closed-circuit rebreathers for scientific diving. Int J Soc Underwater Technol. 2010; 29(2): 73-8. http://dx.doi.org/10.3723/ut.29.073

Starck WA III, Starck JD. From the Bahamas to Belize: probing the deep reef's hidden realm. Nat Geogr. 1972; 149(12): 867-86.

Stone WC. (ed.) The Wakulla Springs Project. Derwood, MD: US Deep Caving Team; 1989; 213 pp.

Stone WC. Exploring underwater with a failsafe diving rebreather. Sea Tech. 1990; (12): 17-23.

Stone B. Rebreather hazard analysis and human factors, or how we can engineer rebreathers to be as safe as OC scuba. In: Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014: 153-72.

Tinker MT, Costa DP, Estes JA, Wieringa N. Individual dietary specialization and dive behaviour in the California sea otter: Using archival time-depth data to detect alternative foraging strategies. Deep Sea Research Part II. 2007; 54: 330-42.

Tomoleoni JA, Weitzman BP, Young C, Harris M, Hatfield BE, Kenner M. Closed-circuit diving techniques for wild sea otter capture. In: Steller D, Lobel L, eds. Diving for Science 2012. Proceedings of the American Academy of Underwater Sciences 31st Symposium. Dauphin Island, AL: AAUS. 2012: 193-9.

Tricas TC, Boyle KS. Acoustic behaviors in Hawaiian coral reef fish communities. Mar Ecol Prog Ser. 2014; 511: 1-16.

Tzimoulis P. 300 feet on computerized scuba. Skin Diver. 1970; 19(9): 28-33.

Vann RD, Denoble PJ, Pollock NW, eds. Rebreather Forum 3 Proceedings. Durham, NC: AAUS/DAN/PADI; 2014; 324 pp. http://media.dan.org/RF3_web.pdf

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.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

Mixed Mode and Mixed Platform Diving

Brett T. Seymour

National Park Service, 12795 W. Alameda Parkway, Lakewood, CO 80228, USA
brett_seymour@nps.gov

Abstract

The subjects of mixed mode and mixed platform dive teams are topics that all diving programs have, or will struggle with as rebreather diving becomes more prevalent in the scientific diving community. It has been a bone of contention for programs working together on joint diving operations, to the point that rebreather divers from an agency whose Dive Control Board (DCB) has approved rebreathers as a diving mode have been forbidden to participate in diving operations, or in some cases not even allowed to dive from another agency's vessels if they were making rebreather dives. It is the opinion of the author that mixed mode dives can be conducted with minimal risk to the participants of a given diving operation. The paper explores the concept of, and offers a template for, mixed mode and mixed platform dive teams and diving operations.

Keywords: rebreather, open-circuit, closed-circuit,

Introduction

What is a mixed mode dive team, and what are mixed platform dives? For the purposes of this discussion a mixed mode dive team is a buddy team where one diver is outfitted with open-circuit (OC) scuba equipment and the other buddy is equipped with a rebreather (either closed-circuit [CC] or semi closed-circuit [SCC]), or where an OC buddy team and a rebreather buddy team are conducting joint in-water diving operations. Mixed platform dives are rebreather dives where the divers are using different rebreather makes or models.

It is recognized that there are several diving environments, profiles, or tasks that may not be conducive to OC/CC mixed teams. In many diving operations the use of mixed teams would negatively impact bottom times, decompression obligations, gas planning between the members of the buddy team if divers were equipped with different diving modes. However, there is a wide-range of diving operations regularly conducted within the scientific diving realm where mixed teams can be utilized safely and efficiently.

Open-Circuit and Closed-Circuit Mixed Teams

To date the vast majority of rebreather divers have followed an OC first training progression where a solid open-circuit skills foundation is laid before the diver receives additional training and experience to progresses into rebreather diving. This provides the rebreather diver the experience and skill set necessary to dive either mode and to recognize problems associated with and the differences between these diving modes. It is the differences and the OC diver's lack of experience with rebreathers that present issues and potential problems for mixed diving operations.

DCB review and approval

As with any diving operational question within the scientific diving community, the subject of mixed mode or mixed platform diving must be reviewed and approved by the agency's Dive Control Board (DCB). Currently, the approved policy regarding this subject in the National Park Service (NPS) Reference Manual (RM) 4 – Diving Safety and Operations Manual, Chapter 4 – Diving Operations, states:

"4.2.4 Mixed Equipment Configurations

> A. It is recognized that dive buddies use dissimilar diving modes or gear configurations for a variety of reasons (previous training, dive objectives, dive task assignments, etc.). The use of dissimilar diving modes or gear configurations on a given dive is permitted within NPS dive operations.
> However, it is recognized that the use of dissimilar gear configurations carries with it the potential for confusion in an emergency. To address this issue, divers are to thoroughly brief dive buddies and others involved with the dive operation on specifics associated with their particular gear configuration and/or diving mode. This briefing will include, but is not limited to:
>
> I. Placement and function of alternate gas sources for buddy access in an emergency
> II. Placement of and access to diver carried cutting implements
> III. Function of buoyancy control device(s)
> IV. Interpretation of information displayed on any diver carried electronics or gauges pertinent to decompression management, gas management, ppO2 display, or other dive related information
> V. Recognition and interpretation of any alerts/alarms produced by dive related electronics or gauges
> VI. Expected buddy response to any alerts/alarms produced by dive related electronics or gauges
> VII. Specialized hand signals
> VIII. Basic problem recognition and response associated with dissimilar gear configuration
> IX. Placement and function of clips, valves, mouthpieces, buttons, hoses, etc. associated with dissimilar gear configuration
> X. How to remove the diver from the equipment if necessary
> XI. Placement of diver carried weight
> *XII.* Actions required to remove diver carried weight"

While this policy is NPS specific, other scientific diving organizations may want to consider it as a template. Regardless, it is the opinion of the author that any DCB can produce safe and effective policy and procedures for mixed mode and mixed platform diving when the following are considered:

Determining factors – environment, profile, and tasks

Environmental factors of the diving environment factor into the use of mixed teams. Diving environments such as high current areas where additional drag associated with many rebreather configurations may be an issue may induce an increase work of breathing and possible $C0_2$ issues for the rebreather diver. Overhead environments such as shipwreck & cave penetrations that require (or at least benefit from) CCR efficiency could preclude a mixed team due to the limitations on the OC diver. Dives where marine life behavior is critical and a lack of bubbles is beneficial, such as natural history photography or filmmaking may preclude mixt mode teams or operations. Likewise, fish transects or counts historically conducted on OC could also prohibit mixed team due to the concern for skewing the dataset. Lastly, the need for increased bottom time on certain depth ranges may discourage mixed teams, or at least mixed buddy teams, with CCR offering both the advantage of gas and physiological efficiency throughout the duration of the dive making it much less efficient for a mixed buddy team due to the OC diver's limited gas supply.

Competent open-circuit diver

The skills and abilities of the OC buddy to pair with the CCR diver are paramount in the decision to dive. Does the OC diver have the experience and in-water composure to essentially lead the dive and adapt to any newly learned equipment location and function on the CCR diver? Are they experienced and component enough to absorb and retain any newly provide CCR equipment and operational deviations such as identifying and perhaps being able to adjust PO_2, the mechanics of the closed-circuit mouthpiece/ or differences in CCR buoyancy characteristics? Can they adapt to the lack of bubbles produced by the rebreather diver and adjust their buddy contact skills accordingly? Newly certified divers or OC divers without a high level of comfort in the water are not good candidates for mixed teams.

Demystify the CCR

What does the OC diver need to know vs what do they want to know? The deck of the boat, in a pre-dive scenario is not the appropriate time to teach the OC diver the ins and outs of CCR diving. Determine what is critical to the dive (emergency air, etc.) vs what can be discussed later depending on interest (i.e. flow path and stack duration). By identifying the few pieces of the equipment configuration that are new to the OC diver such as the dive/surface valve (DSV) or bailout valve (BOV), or manual add buttons, as well as the parts of the equipment familiar to the OC diver, demystifies the CCR and establish a groundwork for proper emergency response (gas sharing, buoyancy compensator (BC) inflation, potential weight ditch). The following, at a minimum, should be identified and demonstrated:

- Emergency air source – shared air, buddy breathing, bailout valve
- Buoyancy – wing or BC inflation
- Weight – intergraded, belt, trim pockets
- Loop / mouthpiece vs OC regulator
- Electronics / heads up display (HUD)
- PO_2 monitoring / adjustment

Open-circuit drives the dive

It is the philosophy of this author that when mixed OC/CC buddy teams are utilized that the OC diver always 'leads' the dive. Due to decompression obligations, gas limitations, etc. the OC diver needs to be competent enough to monitor their own gas management and profiles and make the determining decisions based on their OC planning. In almost every situation, the CC diver will have more bottom time, less gas consumption i.e. the potential for a longer dive. The CC diver, whether performing the primary tasks underwater, or just acting in the buddy role, needs to be prepared to limit both task and duration based on the OC buddies dive planning and execution.

Buddy team are rigid, dive teams can be flexible

In the situation where same mode buddy teams make up a mixed mode dive team, a decision needs to be made on how the team will react if a diver in one of the buddy pairs has a problem that would cause the buddy pair to terminate the dive. Depending on any number of factors specific to a given diving operation, it could be that an issue with any one member of the greater team could terminate the dive for all, but is the opinion of the author that this need not always be the case. An issue requiring a diver to terminate a dive should require their dive buddy to terminate the dive and ascend also, but it does not absolutely require the termination of diving operations by the entire team. These scenarios must be discussed with all participants of the diving operation and addressed on a case-by-case basis.

How do divers share air in an emergency?

It is recognized that under some shallow water diving scenarios, where the diver's onboard cylinders provide sufficient volume for OC bailout, that a rebreather diver may not be required to carry offboard bailout. However, on a mixed mode dive OC divers need to know how they can receive gas in an out-of-gas situation. This dictates an offboard bailout cylinder always be carried by the rebreather dive buddy when diving with an OC dive buddy.

Potential emergency procedures

By demystifying the CCR we lessen the perceived complexity of the system by pointing out the similarities between the different configurations as well as the differences. Most of the items covered in an equipment briefing would also be covered in a gear orientation conducted by two divers using dissimilar OC equipment. The goal is to reduce the information exchanged to what the OC buddy needs to know to conduct the dive, and identify the critical issues associated with emergency procedures; stressing to the OC diver that the rebreather in its basic emergency procedure is very similar to the OC setup. Building on that, we introduce CCR specific emergency procedures such as:

- Bubbles from the loop – The OC diver needs to understand the circumstances when bubbles are expected (during ascent) and volume of bubbles to be expected on a dive (CCR are not without bubbles).
- BOV/OC bailout – The OC diver needs to understand the CCR diver's methods to get off the rebreather in case of failure. This should include the mechanics of the BOV (twist, pin index, lever rotation, etc.) and an understanding of when the loop is closed.
- HUD/Alarm/Alert indications – The OC diver needs to understand that audible or visual alarms or alerts are expected during certain portions of a dive, and that not all flashing lights or beeping noises require a dive to be terminated, though some do. These may include audible alarms or flashing lights from the HUD. It is the responsibility of the rebreather diver to establish what level of clear communication will be used while on the dive and what alarms/alerts/lights will be responded to, and how.
- PO_2 – The OC divers needs to have an understanding of how to check the breathing mixture within the loop of a CCR buddy. In addition, the OC diver should understand the location and ability to manually add diluent or O_2 to the system, if manual addition is part of the rebreather diver's unit configuration.

Mixed Platform Teams

The question in some scientific diving programs/operations is whether mixed platform teams have mastery of their buddies CCR design, engineering, PO_2 control, HUD or electronics? Should they be certified or 'crossed over'? It is the opinion of this author that a higher level of training (i.e., CCR diver) equals a higher level of self-sufficiency. Based on this concept, mixed platform divers should have no issues diving together as long as the following, at a minimum, are addressed:

- Emergency breathing gas – bailout, manual adds, ADV
- Buoyancy – wing or BC inflation, over pressure relieve valve (OPV)
- Loop/Mouthpiece functions
- Electronics/HUD/Alarms/Alerts

Potential emergency procedures

As with the OC diver, mixed platform teams are responsible for communicating the basic expectations of any given HUD light, alarm, or alert. These may go beyond the general notification and into potential problem resolution as the CCR buddy should have a greater understanding of the operations of the CCR.

Conclusions

It is the belief and experience of this author that mixed buddy team, either OC/CC or mixed platform dives can be an effective and productive means of conduction tasks underwater. In the case of OC/CC teams, once the CCR has been demystified and the OC diver understands the system in its most basic form with regard to emergency breathing gas, buoyancy, weight removal/replacement, mouthpiece function, and HUD / alarm indications their comfort level often goes up. They begin to see the systems as a BC with an inflator hose and an overly large mouthpiece. They are also comforted to know that regardless of the CCR, their buddy is carrying an entire offboard stage cylinder that is not being drawn down throughout the dive that can completely be handed off to them in case of an emergency. If they are competent diver, which is required for this OC/CC mixed team, once they get past the perceived complexity they often begin to focus on the benefits of the CCR which leads to additional discussion away from the pre-dive activities.

With regard to mixed CCR teams, the benefit of cross agency, program, or diver interaction far outweighs any bias toward a single CCR make or model. As mentioned earlier, the CCR diver encompasses a far greater level of training and therefore a higher level of self-sufficiency, task loading, and in water time. Once the basics of emergency breathing gas, buoyancy, weight, loop, and HUD/electronics have been examined and demonstrated, the discussion inevitably moves into the engineering, benefits, and feature set of each independent unit. This type interaction encourages continued development and growth with the diving community and industry as a whole.

QUESTIONS AND DISCUSSION

DAVID KUSHNER: I would like to begin the discussion by saying that I am not so sure this is the best group for the discussion. We probably need to reach out to a group of people that are solely open-circuit to get that side of it as well. This group tends to have both experiences.

BRETT SEYMOUR: Good thought. I think we have multiple groups in the room that have different philosophies, and that is what I was looking to get. I was looking to pitch what the Park Service philosophy is and then what other people are doing from the AAUS community or NOAA or USGS.

DAVID KUSHNER: I think that is good but I think that whatever we decide, it would be really good to reach out to groups that are strictly doing open-circuit and see what their views are.

BRETT SEYMOUR: Absolutely.

JEFF GODFREY: One of the things we have been doing over the last few years is to provide an opportunity to try a rebreather in scientific diving courses. During the rescue scenarios, we have been putting a rebreather diver in the water even though the students are not diving with them. That gives them a chance to get some hands-on experience. It is not that big of a deal to add it to the mix.

BRETT SEYMOUR: I found with traveling in my national parks community, that interfacing with open-circuit divers is important since this technology is coming. Somewhat unusual in the National Park

Service is that most of the EMT and medical functions are handled internally. So if you have a dive accident in a national park, you are going to get the Park Service ambulance and/or the Park Service EMT. We try to bring a rebreather into any given project to expose the divers to the technology, along with the management or supervisory level park dive officers. Because they are generally the ones that either are involved in the permitting of diving that goes on in national parks or are going to interface, if there is an accident. The superintendent or management is going to call them, so it is a nice way to expose them to different technologies.

NEAL POLLOCK: Brett, you did a good job telling us how you do it. Can you tell us what kind of problems you have with mixed team operations?

BRETT SEYMOUR: I think one of the biggest problems we have had is people not speaking up and saying what they do not know. When I first started doing it, I would give them a brief. Then I realized I was not going far enough. So I started looking at how I could continually ask them if they have any questions. Aside from in-water, I personally have not had anything that has really been compromised by the mixed team because I am very adamant that the open-circuit controls the dive. So I am very firm about bottom times and such. We will plan the dive, look at tables or discuss tasks based on open-circuit.

JEFF BOZANIC: That was a great job at summarizing the in-water portion, but I have also found in working with mixed teams or groups that are not used to diving rebreathers is it is very helpful to communicate how it is they can help you on areas outside of the in-water emergencies too. Even things like pre-shipping something like absorbent and letting them know that that cannot be stored outside or needs to be stored properly or a special work area to be able to work on rebreathers where you are not going to have to worry about people tripping into electronic components or dropping tanks onto fragile components. Letting them understand what your needs are as well as what your capabilities are in terms of being able to provide assistance or what not underwater. That has gone a long way to helping change people's attitudes from thinking of you as perhaps a superman into something that is a little bit more human, realizing that you are still trying to deal with your own issues and your own problems and your own specialized needs for what you are doing rather than just trying to do everything on your own.

BRETT SEYMOUR: Right. One other thing I did not specifically focus on is the fact that we work in somewhat remote areas. Perhaps not compared to the types of other expeditions, but when you look at some of the places we go in national parks, we can support a whole operation based on what is in the truck. Obviously, the efficiency of the system allows us to go a lot longer. Sellers and I have done trips to Yellowstone National Park or through the Rockies supporting park trainings and stuff for a week carrying what we need and never having to go to a dive shop.

NEAL POLLOCK: Can we get from the group, has anybody had problems with mixed team operations?

SUSANNA PERSHERN: I do not want to say it is a problem, but a thing that I have observed is coming into a mixed team scenario they are automatically assuming that you do not need help or you have got it all together. And you have to really communicate to this open-circuit person that you actually do need their help. And also a big thing for me when you get into the deeper depths it is the time thing. I agree that open-circuit automatically drives the dive, but at the same time, as a closed-circuit diver, I cannot go as fast. I do not want to run my CO_2 up. I do not want to push, push, push. For me, this has been a communication problem. Also, if you have got a lot of gear and you have very limited table space, please let the closed-circuit person put their rebreather down.

RICHARD PYLE: We have done a bunch of mixed closed-circuit diving. We have done some closed-circuit/open-circuit mixed gas diving, but not so much. We have done more mixed teams with closed-circuit/closed-circuit, using different models of rebreathers. When we worked with the NOAA team, we did a pool familiarization session. And I worked with Dave Pence's group using Inspirations. What I found very valuable on expeditions is everyone preparing their rebreather in the same general area; that is where much of the knowledge transfer happens. That is where all the rebreather nerd conversations start, encouraging cross-communication. You learn the basics of where the alarms are during the orientation session, but the informal, "Oh, why are you doing it that way" comes with proximity. That is where I have picked up a much greater understanding of how other systems work.

DAVE CONLIN: Can you talk a little bit about how we do our annual skills demonstrations and where we think we are going with that.

BRETT SEYMOUR: You can talk about it.

DAVE CONLIN: We have annual skills demonstrations. We call it clever diver tricks. And we are trying to move to the point where we are going to do all of those skills on closed-circuit. It is a different paradigm because it is kind of silly if we are diving closed-circuit rebreathers most of the time and then we put on our open-circuit gear so that we can do our annual skills and we put on our CCR. It is a different take on mixed teams, but it is sort of an issue. And what we found is that some of the required elements for an NPS annual skills demonstration do not translate well to closed-circuit rebreathers.

STEVE SELLERS: We do have annual drills that we call our blue card skills; the rest of the park does them as open-circuit. I think the board is trying to figure out do we kind of change the paradigm and make them do those skills in rebreathers and we have done them.

BRETT SEYMOUR: Not just do we recommend it, do we require it and is there any modification to an exam that we have been doing for 40 years now annually? What does that look like? How do we adapt those things to closed-circuit?

STEVE SELLERS: I had something else. I wanted you to relate your experience with the mixed team in the cave.

BRETT SEYMOUR: Thank you. We did a workshop. Part of our training requirements in the National Park Service is that every three years we are required to do a 40 h workshop. Steve and I recently went to north Florida because Devil's Hole or Death Valley has a dive team that works in Devil's Hole for fish counts and such. They had successfully managed to do their 40 h workshop in cave country so Sellers and I went down to support in-water operations. Sellers monitors most of the 40 h programs on behalf of the board. So we were talking about logistics and cave logistics with these individuals; competent, open-circuit cave divers for the most part. So they asked what I was going to carry. I said well, we have a thing in our cave kit, we can go a thousand feet in. We will carry an 80 ft^3 cylinder and that gives us further than any penetration point you will need. They said, well, we are not really sure that that is enough gas. We want you to carry gas for us as well. They were thinking of the rebreather and the stage was my system. What was I going to carry for them? So we had this discussion about, well, you can have all of my gas if you need it if you have a problem in open-circuit. It finally came down to, we would like you to carry another 80 for us. You have an 80 for you. We have an 80 that we have access to. I was like, well, are you going to carry an 80 for me too? How far down this road do we go? I am not a very pushy person and I was there to evaluate and be in the water. So I said, yes, no problem. If that will ease your comfort level, then I will carry two 80s in the cave. What Sellers and I have talked about is that miscommunication. The knowledge of what is gas sharing, and how emergency procedures workout in the open- and closed-circuit worlds was an interesting case of them wanting me to carry enough gas for them, but they were not really concerned about having gas for me. An interesting situation.

JIM HAYWARD: If they are just having thirds, then they have got your reserve on open-circuit. But, actually, I was thinking about the same question essentially for open water. I do not know the capabilities of your units in terms of bailout. If you just have one outboard bailout that you have to give to your open-circuit buddy if they have a failure, does that leave you without any offboard bailout?

BRETT SEYMOUR: Offboard, yes.

JIM HAYWARD: So that is not an unreasonable question. Will you ever consider making the open-circuit divers carry their own? Maybe they are not used to, but might take some training.

BRETT SEYMOUR: I think you start to open the can of what is redundancy on redundancy. So an open-circuit failure, an open-circuit loss of gas, versus an open-circuit loss of gas failure and a closed-circuit loss failure, you are having a two system failure. So does everybody carry, and what if the backup fails. I see your point. When we do it traditionally, I will either carry a 40 or an 80. Most of the time it is a 40 because the stuff that we are doing, as a photographer, I have a different opinion, I am not very interested in the deep stuff because there is not great light. I am much more comfortable with the shallow stuff from a photography standpoint. So I will carry 40 and that will be the reserve gas.

BEN WEITZMAN: I am with the oxygen rebreather group. And we have a few different units, Carlton Cobra and Frogs. Most of us have been cross-trained on both units, but probably our biggest mixed operations come in with our surface support, our dive tenders. That is comprised of some people who are divers. Sometimes it is ourselves. And sometimes it is biologists that are part of the project that we in recent years decided we need to get these people some familiarity and training with the equipment. I am curious about the broader rebreather community regarding surface support and dive tenders, what roles do they play in the program? Are they trained? Do they have some sort of familiarity with the equipment? And has there been any conflict?

BRETT SEYMOUR: We have different levels. Your operational level meets whatever the job is. If we are doing mixed gas closed-circuit stuff it is a different operational tempo than if we are out doing documentation on a shipwreck site at 60 ft (18 m). We will bring in surface support. Doug Kesling has worked surface support for us in the past. Or we will bring in another individual. So we will have that dedicated surface support. Other than that, we generally rely on our team, which is fully versed in closed-circuit and all logistics to stay up and handle emergency, one or two people to stay up to do emergency radio or dispatch kind of a thing. But in terms of a closed-circuit operation, I think for the most part, we would support the logistics on top with people who are in the know with the closed-circuit community.

SIMON MITCHELL: To make a quick point about diver rescue. Largely in response to a question from the AAUS a few years ago, I headed up a committee that looked at diver rescue protocols in an unconscious diver at depth on behalf of the UHMS. We published those guidelines in 2012 so they are available for everyone to see (Mitchell et al. 2012). In terms of closed-circuit mixed teams, in order to be compliant with those, or able to invoke those recommendations for an unconscious diver with a mouthpiece in place on the bottom, the three pieces of information you need to know about a rebreather that might not be the one you were trained on, how to look at what the PO_2 is, how to manually inject diluent, and how to manually inject oxygen. Those are the three pieces of information that need to be exchanged before the dive between the divers using different rebreathers in order to invoke those recommendations. If the mouthpiece is out, you just send them to the surface. But mouthpiece in, those are the three pieces of information you need.

Mitchell SJ, Bennett MH, Bird N, Doolette DJ, Hobbs GW, Kay E, Moon RE, Neuman TS, Vann RD, Walker R, Wyatt HA. Recommendations for rescue of a submerged unresponsive compressed-gas diver. Undersea Hyperb Med. 2012; 39(6): 1099-108.

BRETT SEYMOUR: Great.

NEAL POLLOCK: Do we have anybody else that has mixed team issues or anecdotes?

BRIAN HAUK: We use open-circuit for support divers. When we come up to our first stop, we will launch a surface marker buoy. And they will come down with an intermediate bailout mix for safety purposes. We run them through just those basics, how to read PO_2, HUD displays, how to do a diluent flush, and that kind of thing. We often use ourselves if we are short, crossing CCR divers to open-circuit. And it really helps to have somebody that really knows the unit more than just that basic intro in a pool session. I feel a lot more comfortable if support is from one of our CCR team members.

BRETT SEYMOUR: What operational parameters? Are we talking the deep stuff or a 60 ft (18 m)?

BRIAN HAUK: At least moderate decompression. We do have that basic thing. But we have been in situations where you do not have somebody that is highly trained like that. You just have an open-circuit diver. You run them through the basic stuff. It is much more comforting to have somebody that is either a technical diver even better or a rebreather diver on that same unit. So when it is really push comes to shove, they know what to do in that situation.

DAVE CONLIN: Are your support divers coming down single or in pairs?

BRIAN HAUK: In pairs.

LIZ KINTZING: Do you use them every time?

BRIAN HAUK: Anytime requiring decompression, we have to have them in a chase boat. We will have a secondary boat with those divers in it. And various protocols, depending on what kind of surface floats come up and colors and that kind of thing.

BRETT SEYMOUR: How about mixed platform?

BRIAN HAUK: We have done that as well with the Inspirations and Poseidons. Before, as Rich Pyle was saying, we will get in the pool and run through those basic scenarios. As Rich also talked about, where you really learn those things is you spend weeks diving with these people and talking story about it and figuring the ins and outs out. But that basic pool session gives you enough, for me to at least feel comfortable in the water and be able to handle it. I think it does help to have at least like a buddy team on those same units rather than you have like everybody on their own unit and nobody really knows another unit that well.

BRETT SEYMOUR: On mixed operations platform to platform is that a project decision? Does it require board approval? Or is it so it goes up in and the board approves the operational plan which may or may not include mixed teams?

BRIAN HAUK: The board has certain criteria of what they are going to accept.

BRETT SEYMOUR: Have you done any mixed team that does not require decompression. I do not want to say normal operations, but more in line with mapping operations or something that does not involve required decompression?

BRIAN HAUK: Yes, but not for CCR too much. We have had open and closed-circuit like that for proficiency dives and that kind of thing.

GREG McFALL: I just wanted to add something to that. We cover all the basic parameters that we have already talked about, but the point of getting in the pool, from my perspective, is that you are trying to find where potential problems might be before they occur. So if you are going to share offboard gases, are your connectors the same? Do you have the same whips? And if not, can you run another whip to share gases with someone on a different platform? You are really trying to find the problems before they happen.

RICHARD PYLE: Echoing what Greg said, I hope what I said before did not sound like dismissing the pool session. I think that it is incredibly valuable. I just wanted to say that on expedition, you can continue that cross-familiarization in real time.

DAVE PENCE: As Rich has pointed out, we have had experience with a variety of scenarios over the years. In the very early years there was no option but to engage in mixed teams because there were pretty much only a couple of rebreather divers in existence. If you were going to dive in a buddy situation, you had to come up with some sort of decision-making parameters for what is important for your buddy to know in both directions. In expeditionary situations there is a long history of mixed teams. And I think you have done an excellent job of hitting all of the salient points. How you address those is always going to be an operational decision based upon the resources and timeline that you have available. Taking that to an extreme, in expeditionary situations there have been a lot of situations where we really have not been able to provide one of our safety divers or one of our team divers as the topside support divers and have had to work with indigenous personnel in order to provide some semblance of response. It all comes down to what a person is capable of doing when you decide on potential options. Is this someone who is sophisticated enough to know red versus yellow and whether the normoxic trimix cylinder is better to send down than the oxygen cylinder? If not, you better have it all with you on the bottom and make sure that your team can take care of those situations. Ultimately, the role of the topside support is incredibly plastic based not only upon your resources but upon their experience level.

BRETT SEYMOUR: It is not a discussion on topside, but I would say that the Park Service accident a couple years ago gave us a take-away message that having a single person topside is perhaps not enough. In our situation a single person on the deck would not have made things go as smoothly as it did. Having multiple persons, we purposely staged people to go in to cover that scenario, but I think coming out the back end and saying a person on the deck to be able to notify EMS, in our case call dispatch and move and grab and identify, clearly -- would it have worked? Yes, eventually. But would it have worked in the same manner that it did and would the outcome be the same? Probably not. There are some really interesting lessons learned on operations that inform the theory of leaving a person on the deck to handle everything.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

Factors in Decompression Stress

Neal W. Pollock

Divers Alert Network and Center for Hyperbaric Medicine and Physiology,
Duke University Medical Center, Durham, NC
npollock@dan.org

Abstract

Dive computers increasingly control the decompression profile of dives. While the algorithms employed provide useful insight, they are blind to many of the factors that can affect decompression risk. It is important for divers to appreciate the dynamic impact of what may positively or negatively affect risk to respond accordingly. Risk factors are fit into four categories for the current discussion: dive profile, thermal profile, exercise profile, and predisposition factors. Understanding the potential effects of different factors and interactions between factors can help divers actively manage risk to ensure safe outcomes.

Keywords: algorithms, decompression sickness, diving, exercise, health, safety, thermal

Introduction

The computation of decompression obligations has been handled by a small number of mathematical models for much of the last century. Evolution in recent decades, however, has produced an array of deterministic algorithms and derivations to regulate human diving with personal dive computers. Gas content models, such as those of Haldane and Buhlmann, focus on the mass uptake and elimination of inert gas based on half-time computations for different tissue compartment constructs. Bubble models, such as Yount's varying permeability model (VPM), and then Wienke's reduced gradient bubble model (RGBM) that evolved from it, focus on efforts to control bubble formation through the decompression process. The reality of all models currently integrated into commercially available dive computers is that they base the assessment almost exclusively on the pressure-time profile of a dive. While this is almost certainly the most important element and can provide excellent guidance, inert gas uptake and elimination, bubble formation, and ultimately safety, is influenced by a much wider array of factors.

The thoughtful diver can alter the risk profile of a given exposure by attending to the influencing variables. We need to promote this thoughtfulness, since even with all our tools, decompression sickness (DCS) does still occur. The scientific diving community, widely held as one of the safest subsets of the diving world, still reports a decompression illness (DCI) incidence rate of 0.324/10,000 person-exposures (Dardeau et al., 2012). The higher risk in other communities, or even in the scientific diving community for more extreme exposures such as many planned for rebreather diving, makes consideration of both risks and mitigation strategies critical.

Contributors to Decompression Stress

The variables that that can affect decompression stress are clustered into four broad categories for the current discussion: dive profile, exercise profile, thermal profile, and predisposition factors (Figure 1).

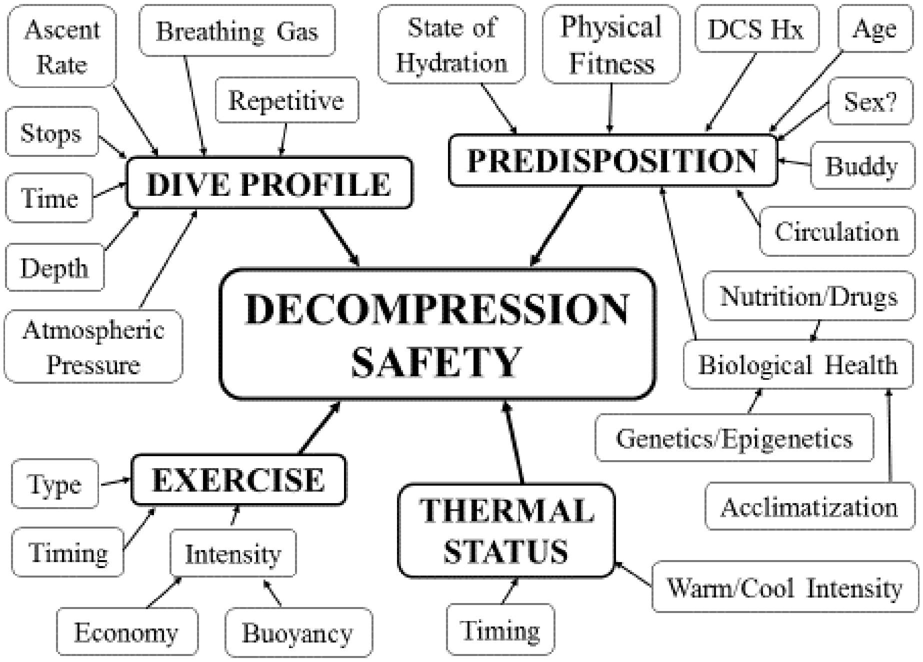


Figure 1. Factors affecting decompression safety.

Dive profile

As stated earlier, the dive profile has the greatest influence in establishing the degree of decompression stress of a given dive. All other factors may work against decompression safety, but without a profile that generates significant decompression stress, DCS will not develop. The depth-time profile is critical, including time spent at given depths, ascent rate, stop depth(s), stop duration(s), and the breathing gas(es) used. The time since and specifics of recent diving exposure(s) can alter the impact of these variables. Subtler effects are created by the water density, fresh or salt, and the surface atmospheric pressure. Explaining the last point, the surface atmospheric pressure is primarily determined by altitude, but there is also a minor influence from the fluctuations in barometric pressure. All other factors being equal, lower atmospheric pressure at the surface means that a greater decompression stress will be produced for a diving exposure.

Dive profile variables are the most easily quantified, thus readily incorporated into dive computer algorithms. Algorithm adjustments are thus typically indexed to these variables, even for factors that are related to the dive profile in more complex ways (all that follow).

Exercise

The exercise profile of a dive includes three key factors: the type of exercise, the timing relative to the dive, and the intensity of the exercise. The potential variability in each of these parameters makes the net effect difficult to evaluate. Ultimately, the same type of exercise can have different influences based on timing and/or intensity. In the broadest sense, exercise during the descent and bottom phase of a dive will promote circulation and increase inert gas uptake, effectively increasing the subsequent decompression stress. Conversely, light to modest exercise during the ascent and stop phase will increase circulation at a point that promotes inert gas elimination, and can thus reduce decompression stress. There is, however, a dualism in the effect of exercise that complicates the picture. While light or modest exercise during the ascent and stop phase may promote the orderly elimination of inert gas to reduce decompression stress, higher intensity effort, particularly if high joint forces are involved, can promote bubble formation and increase the effective decompression stress (Jankowski et al. 2004; Dujic et al. 2005).

The physical demands of diving will vary not only as a function of the absolute conditions of each dive, but also as a function of the skill and equipment configuration of the diver. For example, a diver with more streamlined equipment and better control of his or her buoyancy will work much less than a diver not so well prepared.

Measuring exercise intensity to inform a decompression algorithm is difficult. While heart rate, ventilatory rate, or ventilatory exchange can all reflect exercise intensity, each measure can also be at least partly confounded by excitation and inexperience independent of exercise intensity. It is not clear how to interpret such data, even if it could be easily collected. While some manufacturers have begun to measure heart rate, there are not yet any dive computers that evaluate exercise intensity to incorporate it into a decompression algorithm in a meaningful way.

Thermal status

The thermal status of a diver can have substantial influence on decompression status. A variety of reports have documented the effects. Dunford and Hayward (1981) demonstrated that keeping divers warm throughout dives resulted in higher post-dive Doppler bubble scores. Shields and Lee (1986) documented an increased rate of decompression sickness in North Sea divers using hot water suits vs passively insulated drysuits. Mekjavic and Kakitsuba (1989) showed how post-dive cooling can effectively prolong the risk window for developing symptoms of DCS.

More recently, a study was conducted by the US Navy Experimental Dive Unit (NEDU) in a water-filled hyperbaric chamber to evaluate the impact of the timing of thermal status (Gerth et al. 2007). Dives were divided into descent, bottom, ascent and stop phases, prolonging the latter so it would be possible to increase bottom times if justified by the interim results without compromising the experimental design. The water temperature was held at 97ºF (36ºC) for the 'warm' condition and 80ºF (27ºC) for the 'cold' condition (probably more fairly described as 'cool'). All dives were conducted to 120 fsw (37 msw) depth. Dives were carried out with both phases matched ('warm/warm' and 'cold/cold') and with mismatched phases ('warm/cold' and 'cold/warm'). The greatest differences in DCS were evident between 'warm/cold' and 'cold/warm' exposures (Figure 2). The 'warm/cold' condition, with a bottom time of 30 min, yielded a DCS rate of 22% (7/32 subject-exposures). In contrast, the 'cold/warm' condition was extended out to a bottom time of 70 min and yielded a DCS rate of only 1.3% (2/158). Even if the effects of this study are exaggerated by the prolonged ascent/stop phase, the results document a dramatic impact of the timing of thermal status differences.

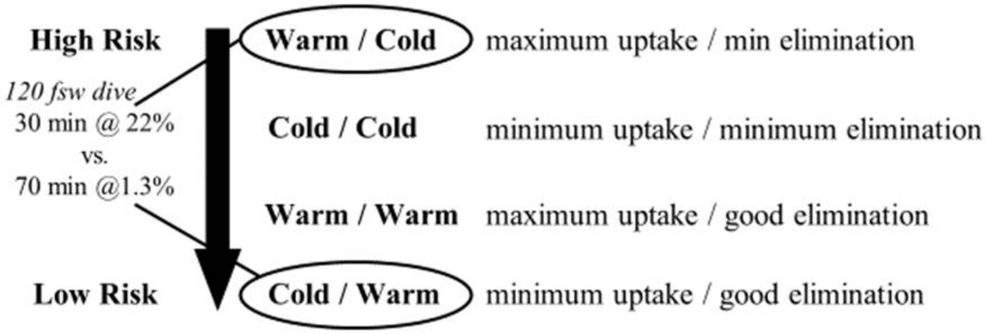


Figure 2. Thermal status and decompression stress (Gerth et al., 2007)

Diver thermal status will almost certainly be measured in the future and the results incorporated into decompression algorithms. At the current time, however, there is one dive computer beginning to test the concept with a single skin temperature measure made with a sensor incorporated into a chest strap. This is a step towards thermal status monitoring, but a very small one. Meaningful monitoring will take numerous sensors and meaningful integration will require a tremendous amount of data collected on thermal status and decompression outcomes to learn how algorithms might appropriately be altered.

It should be noted that measuring water temperature, as many dive computers do, in no way captures the thermal status of a diver. This is easily demonstrated by the fact that the diver could be wearing anything from a bathing suit to a well-insulated drysuit with active heating undergarments.

Predisposition

Predisposition is something of a catch-all category, including an array of factors that can influence the ultimate decompression stress experienced by an individual for a given exposure. The factors depicted in Figure 1 are not ranked in any order of importance. The impact of each can range from negligible to substantial for a given individual and/or exposure. Additional research is required to quantify the individual effects, let alone the integrated impact. None of these parameters can currently be quantified sufficiently to incorporate into decompression algorithms in a meaningful way. Understanding the potential impact, however, can help divers consider and manage risk beyond dive computer guidance.

State of hydration

The maintenance of a good state of hydration is important for health, and important for diving health. Limited research has shown that a state of dehydration can increase the risk of DCS in a swine model (Fahlman and Dromsky 2006). Excessive hydration, though, can also create risk, such as promoting immersion pulmonary edema. It is probably fair to say that an unreasonable degree of attention within the diving community has focused on dehydration as a central factor in decompression stress. This may arise from two realities. First, since fluid shifts and indications of marked dehydration can be a consequence of DCS, the observation of this condition can lead to some confusion over cause and effect. Second is the human desire on the part of the diver to find something to blame for a case of DCS. The fact that a similar dive profile can be completed many times without incident and then result in DCS is disturbing. It is comforting to blame a single factor that can be controlled, even if this is more wishful than factual. It is important for drivers to realize that a multitude of factors can subtly affect the risk on any one dive. Understanding that a range of factors can play a role gives the diver more control in influencing the ultimate risk.

Physical fitness

Divers should have sufficient levels of physical fitness to meet the normal demands of diving with sufficient reserve capacity to handle reasonable additional emergent demands. As an additional benefit, there are data indicating that higher levels of physical fitness are associated with a lower risk of DCS. Human studies have reported fewer post-decompression bubbles following the completion of an exercise program (Powell 1991) and in subjects identified as having a greater aerobic capacity ($VO_{2\ max}$) (Carturan et al. 1999). Animal studies have found a lower DCS rate and severity in treadmill trained pigs vs untrained counterparts (Broome et al. 1994) and reduced bubble formation and improved survivability in exercise-trained rats exposed to severe decompression stress (Wisloff and Brubakk 2001).

DCS history

A history of DCS may indicate a greater predisposition, either physiologically or behaviorally, for an individual. The importance of history may also extend to a buddy since their activity, favoring risk or conservatism, can influence the outcome for others in a group. A diver who experiences DCS may be motivated to alter practice in a number of ways to substantially reduce future risk. A diver who does not take responsibility or make meaningful change, either by blaming it on a convenient scapegoat factor or calling it a fluke, may well be at substantial risk of reoccurrence since at least some susceptibility has been demonstrated.

Age

The impact of increasing age is difficult to assess since it may be confounded with reduced levels of physical fitness, changing health, and changing practice. Increasing age is associated with increased bubble formation, and this potentially indicates a reduced tolerance for decompression stress.

Sex

There is no compelling evidence in the diving literature to confirm that sex plays a role in the development of DCS. This runs contrary to a limited amount of data from hypobaric chamber exposures which suggest that the physiological risk may vary somewhat across the menstrual cycle, specifically that the risk may be slightly elevated during the first part of the cycle. This could be an artifact or specific to altitude exposures, but it could also be real and reflect that differences in individual control confounds the observations. Inside tenders generally do not control the hypobaric exposure; divers typically have greater input with a diving exposure. Practically speaking, even if women do have a slightly elevated physiological risk in comparison to males, active decision-making that favors conservative practice may be more important in conferring enhanced protection.

Circulation

Compromised circulation resulting from prior injury, physical activity, body positioning, or even dehydration, has been viewed as a possible risk factor, but with little empirical evidence.

The presence of a patent foramen ovale (PFO) has the potential to alter circulation by allowing a volume of blood to reach the systemic circulation without undergoing filtration through the lung. PFOs have been identified as a risk factor in serious DCS. Perspective is required, though, for this discussion. It is important to understand that while the frequency of all PFO is high, the incidence of serious DCS is low, so the relationship is not simple. The degree of patency is the first consideration. A 'probe patent' PFO is found on autopsy, when a probe can be worked through the septal wall between the right and left atria of the heart without damaging tissue. The effective opening in such a case, however, may be extremely small. At the other end of the spectrum is the large 'physiologically patent' PFO, large enough so that substantial volumes of blood may pass through with no impediment. The frequency of all PFOs is on the order of 25%, put physiological patency, and certainly extreme physiological patency involves a much smaller subset. It is also important to remember that bubbles must be in the circulatory stream for a physiologically relevant PFO to have impact on bubble distribution. A final point to remember is that the PFO is only one way to move bubbles into the systemic arterial system. They can also be shunted across the lung, more so with exercise (Eldridge et al., 2004). While the presence of a PFO may be important in some cases, the more effective step to increase decompression safety in all divers is to follow dive profiles that effectively minimize bubble formation.

Biological Health

A host of factors falling under the category of biological health may influence the decompression stress of a given exposure. Some probably play minor roles, and some potentially play important roles that have not yet been fully defined. Nutritional status, for example, is important for general health and physical fitness. While research on nutrition and diving is limited, it is possible that it affects decompression safety. One study assessed the relationship between cholesterol levels and decompression-induced bubbles. Doppler ultrasound was used to classify the 30 subjects as either "bubble-prone" or "bubble-resistant." It was found that, on average, bubble-prone subjects had higher total blood cholesterol levels than the bubble-resistant subjects (Webb et al. 1988). Such effects could be linked to age, physical and medical fitness, general or specific nutritional status, or other factors, but it is an area requiring additional research.

The potential interaction of drugs is another area requiring more research data. There is a marked dearth of information on effects or side effects of drugs in relation to diving. This will be difficult to overcome given limited research resources and an almost infinitive combination of drugs, dosing, and combinations of drugs and dosing.

Genetic predisposition and epigenetic expression likely also play a role in both susceptibility and magnitude of the response to decompression stress. This is an area just beginning to receive research attention. It is possible that future understanding will improve diagnostic capabilities both in advance and following insult.

Acclimatization

Acclimatization is defined as adaptive change in response to repeated natural exposure. The effect may be positive or negative. Repetitive diving could influence decompression stress, and not just through the presence of residual inert gas. A positive acclimatization could produce a reduction in the biochemical response, effectively a desensitization, to decompression stress that could reduce the magnitude of the insult. A negative acclimatization could produce a heightened response, effectively a sensitization, to decompression stress. The published data relevant to diving are conflicting, which may in part be a reflection of how divers dive. This can be seen in a typical dive series. In most cases, the initial dives are relatively conservative, with subsequent exposures increasing in intensity. In the simplest terms, it is uncommon for the most extreme dive to be conducted on the first dive of a series. The effect of positive acclimatization could easily be masked by patterns of increasing exposure intensity.

One study attempted to address the potential confounding by evaluating post-dive bubble formation following identical dives conducted on four consecutive days. The dives were known to produce substantial bubble loads with relatively little DCS (60 fsw/18 msw for 47 min bottom time, with moderate exercise sustained throughout the dives). The results are summarized in Figure 3. They demonstrated an increased likelihood of observing relatively lower bubble grades than relatively higher bubble grades on subsequent days of diving (Zanchi et al., 2014). As an important practical point, this does not provide license for divers to act more aggressively over a dive series, but it may help to protect against small errors in practice that can occur.

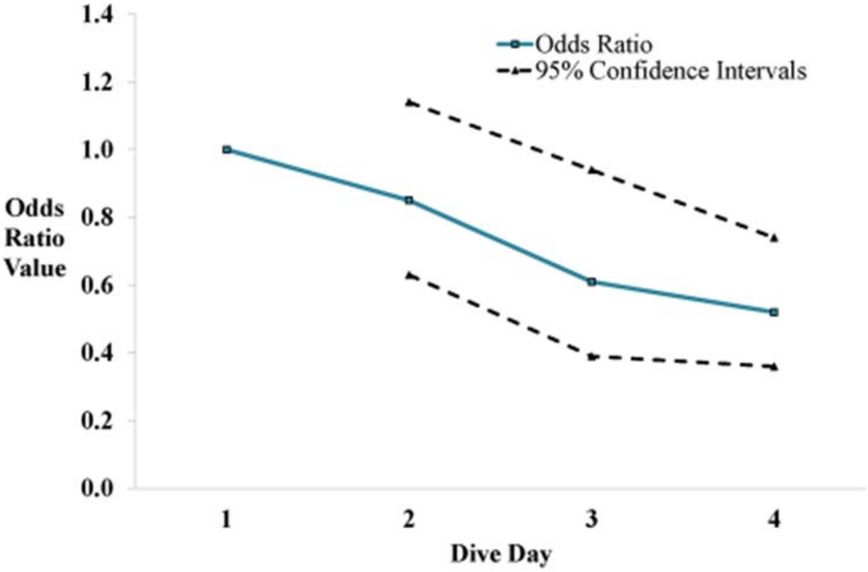


Figure 3. Assessment of a linear dose-response relationship for the odds (logit-risks) of having a higher-grade bubble over four consecutive days of diving referent to Day 1 (Zanchi et al., 2014).

Managing Decompression Stress

Dive profile

Dive computers have now largely taken over the control of dive profiles, running an array of algorithms. Complicating the picture, many designers and/or manufacturers have modified the base algorithms, frequently providing no details about the modifications. Most of the algorithms incorporated into commercially available dive computers provide adequate protection for typical exposures, but the fact remains that DCS can develop in people who dive within the limits of decompression models. The actual risk results from the complex interplay of the dive profile, the timing and intensity of thermal and exercise states, and a host of individual factors described above. For some, the level of risk associated with current decompression algorithms is acceptable. Others, individuals or institutions, may desire additional buffers to address differences in susceptibility or simply for risk tolerance. This brings us to conservative settings.

Many dive computers offer some degree of user-selectable conservatism, which will alter the limits displayed. A variety of conservatism protocols have been implemented, some more intuitively clear than others. One computational method of conservativism that is easy to both quantify and understand is gradient factors, a construct credited to Erik Baker.

Gradient factor settings adjust exposure limits to become fractions of another limit. Gradient factors are commonly used with the Bühlmann algorithm, a well-researched set of decompression procedures for which the underlying source code was openly released to the community. The open release allowed public scrutiny to fully evaluate the algorithm and resulted in corrections that were incorporated into subsequent revisions.

Gas uptake and elimination can be predicted using exponential half-times. To illustrate: a diver descends to a fixed depth and stays there. One half-time is the time it takes for a tissue to take up inert gas equaling half the difference between the inert gas content in equilibrium (saturated) at the surface pressure and the gas content of the tissue if saturated at the ambient pressure of the current depth. The next half-time eliminates half of the remaining difference, and so on. Complete equilibration is achieved in about six half-times. The complication is that body tissues take up and eliminate inert gases at differing rates. The fastest tissues are the lungs, which achieve equilibrium almost instantly. Blood is another extremely fast tissue, followed by the brain. The slowest tissues are those that are relatively poorly perfused, such as ligaments and cartilage, or those that are relatively poorly perfused and have a high capacity for inert gas uptake, such as some fat tissues.

Algorithms will typically include computations to represent multiple tissues. Each half-time used in an algorithm is referred to as a "compartment." A given compartment may not equate to an actual tissue, but the intent is to use a collection of different half-time computations to estimate what happens throughout the body.

Robert Workman coined the term “maximum value,” shortened to “M-value,” in the mid-1960s when he was conducting decompression research with the U.S. Navy. Albert Bühlmann and other modelers also used the term. The M-value is a theoretical construct that describes the maximum degree of supersaturation (gas pressure greater than the ambient pressure) a given tissue can tolerate during ascent before an orderly elimination of inert gas is replaced with a negative outcome. M-values can be predicted for any tissue compartment construct. Faster tissues have higher M-values based on the expectation that they can tolerate higher degrees of supersaturation than slower tissues, in part because their fast clearance rate means that peak levels will be transient.

The computational power of dive computers is essential for determining the status of multiple compartments in real time and adjusting the exposure limits based on whatever compartment is deemed most critical - the controlling compartment - at any point in the process. This is important since modern divers rarely follow uncomplicated square profiles. Instead, they frequently follow complex descent-ascent profiles, relying on the dive computer to keep track of their decompression status.

While the M-value is a useful concept, it is now known that bubbles and even DCS can develop in exposures within M-value limits. This is where conservatism factors become important. Knowing that theoretical limits are not universally safe, additional conservatism can be added by adjusting the allowable limits during decompression (ascent). The dive computer displays the revised guidance to be followed. Such adjustments can be made with strategies that mislead the computer. For example, the amount of inert gas in the breathing supply could be set higher than it really is (if user-adjustable capabilities allow), or nitrox could be breathed while using a computer set to air. Alternatively, the surface pressure could be set lower than the actual pressure to prompt more conservative computations. The problem with this approach is that undesirable side effects can result. For example, if a diver is breathing more oxygen than the computer expects, it will not provide the warnings about excessive oxygen exposure that it would if the correct oxygen levels were registered.

A better alternative is to limit the severity of exposures while fully informing the model. This is done with gradient factors, which are defined by two values. The first number of the pair ('GF_{low}') represents the percentage of the M-value that establishes the first stop during ascent; the second number ('GF_{high}') is the percentage of the M-value not to be exceeded at any point during surfacing. The dive computer effectively draws a straight line between the two, creating the ascent slope.

Dive computers that incorporate gradient factors typically provide either a limited number of choices or allow fully user-adjustable ranges. Figure 4 shows two example settings. The 0% line on the percent of

M-value scale (Y-axis) is the point of no supersaturation; this can be thought of as the bottom depth from which a diver will depart to surface. The 100% line corresponds to the M-value limit. The 15/85 setting (dashed line) may be selected by someone who believes in deep stops typically associated with bubble models and has some confidence in being bends-resistant. The first stop at only 15 percent of the M-value in a typical bounce dive (one in which most tissues do not reach saturation) likely ensures that inert gas uptake will continue in the intermediate and slow tissues during the stop since they are almost certainly below saturation at the stop depth. Allowing the supersaturation to reach 85% of the M-value during surfacing provides a modest buffer from the arbitrary theoretical limit. It may be sufficient in some cases, but it might not be enough for susceptible individuals or if factors not measured by the dive computer act to increase the risk. Finally, the fairly steep nature of the curve means that there is a high rate of relative pressure change near the surface, where current knowledge indicates that a slow rate of ascent is safer.

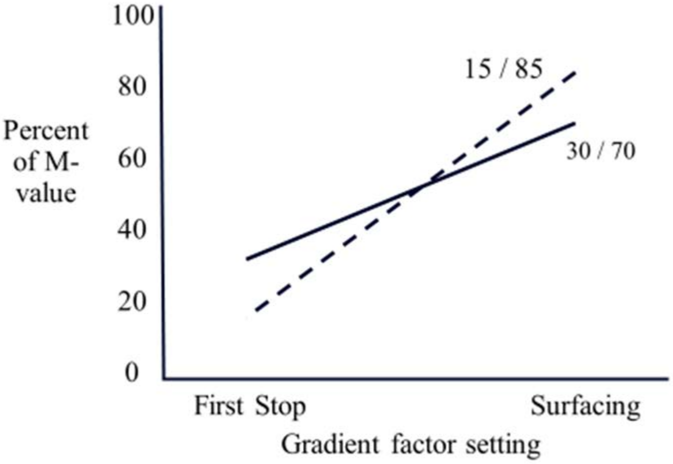


Figure 4. Depiction of stops and ascent slope computed for different gradient factor settings.

In comparison, the 30/70 setting (solid line) brings the diver farther off the bottom for the first stop, which reduces ongassing during the ascent. Reaching only 70% of the M-value during ascent provides a greater buffer for decompression safety, and the shallower slope produces a reduced rate of pressure change in the critical near-surface zone.

Some divers will not appreciate the need to incorporate additional conservatism, particularly if they have not experienced decompression problems in the past. It is important to remember, though, that numerous variables can affect the real risk of every individual and for every dive. Extra conservatism is less punitive that a higher risk of DCS.

Exercise profile

Exercise intensity should be kept as low as possible during the descent and bottom phases of a dive. Mild exercise — on the order of no more than two to three times resting effort (2.0-3.0 metabolic equivalents [MET]), and with very low joint forces —is appropriate during the upper ascent and stop phases of a dive to help increase the rate of inert gas elimination. Too much or too intense exercise, however, can have negative effects. Exercise involving high joint forces should be avoided as long as possible after a dive. If post-dive exercise is unavoidable, dive profiles should be conservative enough to minimize the overall risk.

Exercise that employs high joint forces such as heavy gear lifting or running should be avoided or delayed following dives. If obligatory exercise such as stair climbing in full gear is required, the hazard can be lowered by reducing the severity of the dive profile. This can be done by reducing the dive depth, minimizing exercise during the descent and bottom phases, maintaining light exercise (two or three times resting effort) during the ascent and stop phases, and/or prolonging stop times. The impact of the post-dive exercise can be reduced by delaying the climb out, making it a slow climb out or taking multiple (slow and easy) trips to recover gear.

Safety may also be increased by maintaining a high level of physical fitness. Optimal body composition reduces the amount of ballast weight that has to be carried to achieve neutral buoyancy and, in the case of the obligatory post-dive climb out, reduces the absolute effort required.

The biggest practical challenge typically arises with efforts to schedule physical training activity around busy diving schedules. While limited findings suggest that a single bout of high intensity exercise conducted 24 hours before diving may have a protective effect (Dujic et al 2004), the data concerning exercise closer to the start of diving are fairly confused. Figure 5 summarizes what is probably reasonable and conservative advice.

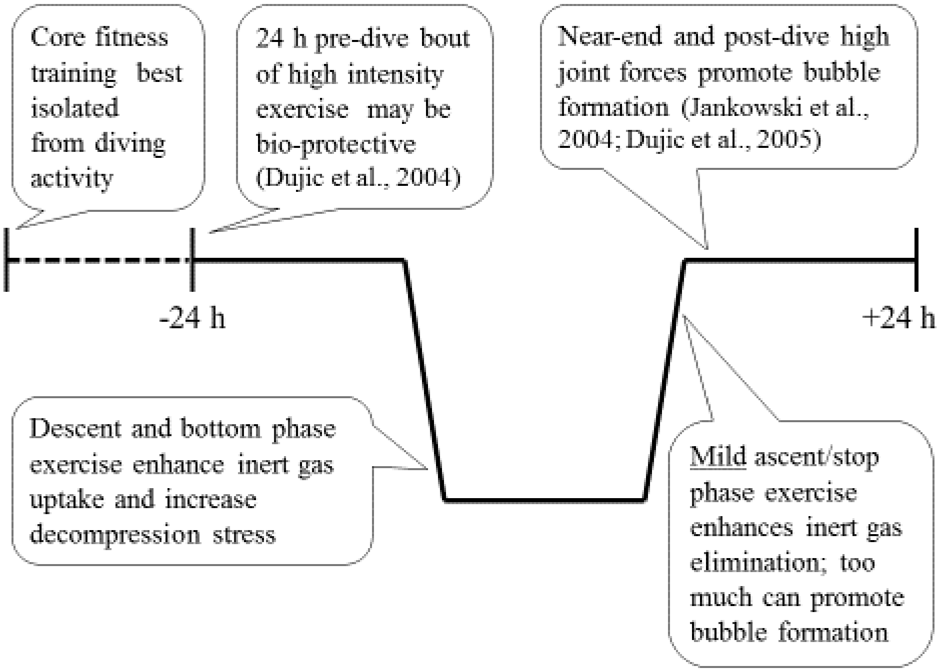


Figure 5. The timing of exercise and decompression stress.

Thermal profile

Maintaining a neutral thermal status during the descent and bottom phases - certainly avoiding unnecessary overheating - and trying to achieve a mild warm status without high intensity exercise during ascent will produce the lowest risk of DCS. The difficulty comes in reconciling optimal practices for decompression safety with divers' desires and normal practices. It is common for divers to want to warm themselves before the start of a dive in anticipation of becoming colder as the dive proceeds. Wetsuit divers might want to pour warm water into their wetsuits or gloves before a dive. Others might want to place chemical hot packs at different points in their suits. More recently, active heating garments have become available for both wetsuits or drysuits. The problem remains with any of these strategies, increasing inert gas uptake early in the dive when uptake is already highest. Since warm water and chemical hot packs lose their effectiveness over time and active heating systems can weaken or fail, the warm-cool pattern associated with the greatest risk of DCS can also develop.

Active heating garments can have legitimate value, but should be used thoughtfully. Warming should never be greater than needed, and consideration should be given to a reduced or low setting early in the dive and a slow increase in warming during ascent. Caution is required in increasing active heating during ascent since gas solubility decreases in tissues as they warm, potentially promoting bubble formation before perfusion increases sufficiently to remove the gas.

Divers must also keep in mind that post-dive warming can also influence decompression risk. Indulging in rapid post-dive warming, such as by taking a hot shower or getting into a hot tub, also decreases the tissue solubility for inert gas and can promote skin symptoms.

Ultimately, divers need adequate protection to preserve clear thinking and physical performance, but they also need to be aware of decompression hazards that can be imposed by thermal manipulation. For many individuals, passive systems will be adequate and appropriate for effective physical and cognitive performance. For those that need or choose active warming systems, thoughtful use is vital, recognizing that they can increase decompression stress even if they work correctly, and that they may increase decompression stress substantially if they fail.

Predisposition profile

Most personal factors that contribute to decompression stress can be modified. Maintaining reasonable levels of physical fitness, nutrition, restfulness, and hydration can contribute to good health and good diving health. Good health can reduce physical limitations and the need for drug therapies. If any drugs are required for health reasons, medical approval prior to use with diving is important. If they are deemed compatible and appropriate to test with diving, careful and monitored evaluation under benign conditions should be followed by cautious, progressive testing under a slowly evolving range of conditions.

Selection of diving partners and teams should consider compatibility of goals and risk tolerance, skills, knowledge, and capabilities. A shared understanding of both risk and best practices can improve operations and readiness.

Conclusions

Implementation of sound practice can help to ensure safe outcomes even with a wide range of susceptibility and real time events. Divers must remember to be conscious of myriad factors that can alter risk and build in buffers to manage their diving appropriately. The thoughtful and well-informed diver knows far more about conditions that may affect real-time risk during a dive than our current dive computers do — and likely far more than dive computers will for many years to come. Ultimately, the best way to reduce decompression stress on any dive is to manage all the contributing factors to push the final balance well onto the side of safety.

References

Broome JR, McNamee GA, Dutka AJ. Physical conditioning reduces the incidence of neurological DCI in pigs. Undersea Hyperb Med. 1994; 21(suppl): 69.

Carturan D, Boussuges A, Burnet H, Fondarai J, Gardette B. Circulating venous bubbles in recreational diving: relationships with age, weight, maximal oxygen uptake and body fat percentage. Int J Sports Med. 1999; 20(6): 410-4.

Dardeau MR, Pollock NW, McDonald CM, Lang MA. The incidence rate of decompression illness in 10 years of scientific diving. Diving Hyperb Med. 2012; 42(4): 195-200.

Dujic Z, Duplancic D, Marinovic-Terzic I, Bakovic D, Ivancev V, Valic Z, Eterovic D, Petri NM, Wisloff U, Brubakk AO. Aerobic exercise before diving reduces venous gas bubble formation in humans. J Physiol. 2004; 555(3): 637-42.

Dujic Z, Palada I, Obad A, Duplancic D, Bakovic D, Valic Z. Exercise during a 3-min decompression stop reduces postdive venous gas bubbles. Med Sci Sports Exerc. 2005; 37(8): 1319-23.

Dunford R, Hayward J. Venous gas bubble production following cold stress during a decompression dive. Undersea Biomed Res. 1981; 8(1): 41-9.

Eldridge MW, Dempsey JA, Haverkamp HC, Lovering AT, Hokanson JS. Exercise-induced intrapulmonary arteriovenous shunting in healthy humans. J Appl Physiol. 2004; 97: 797-805.

Fahlman A, Dromsky DM. Dehydration effects on the risk of severe decompression sickness in a swine model. Aviat Space Environ Med. 2006; 77(2): 102-6.

Gerth WA, Ruterbusch VL, Long ET. The influence of thermal exposure on diver susceptibility to decompression sickness. NEDU Report TR 06-07. November, 2007; 70 pp.

Jankowski LW, Tikuisis P, Nishi RY. Exercise effects during diving and decompression on post-dive venous gas emboli. Aviat Space Environ Med. 2004; 75(6): 489-95.

Mekjavic IM, Kakitsuba N. Effect of peripheral temperature on the formation of venous gas bubbles. Undersea Biomed Res. 1989; 16(5): 391-401.

Powell MR. Exercise and physical fitness decrease gas phase formation during hypobaric decompression. Undersea Biomed Res. 1991; 18(suppl): 61.

Shields TG, Lee WB. The Incidence of Decompression Sickness Arising from Commercial Offshore Air-Diving Operations in the UK Sector of the North Sea during 1982/83. Dept of Energy and Robert Gordon's Institute of Technology: UK, 1986.

Webb JT, Smead KW, Jauchem JR, Barnicott PT. Blood factors and venous gas emboli: surface to 429 mmHg (8.3 psi). Undersea Biomed Res. 1988; 15(2): 107-21.

Wisloff U, Brubakk AO. Aerobic endurance training reduces bubble formation and increases survival in rat exposed to hyperbaric pressure. J Physiol. 2001; 537(Pt. 2): 607-11.

Zanchi J, Ljubkovic M, Denoble PJ, Dujic Z, Ranapurwala SI, Pollock NW. Influence of repeated daily diving on decompression stress. Int J Sports Med. 2014 Jun; 35(6): 465-8.

QUESTIONS AND DISCUSSION

BRIAN HAUK: Just to comment. We looked at RGBM for a while as an algorithm to use. And Bruce Weinke was working up at Los Alamos labs. And he came down and I kept asking -- my specialty is asking dumb questions, and I kept asking.

NEAL POLLOCK: For the data?

BRIAN HAUK: Yes. And basically, he kept throwing up incredible equations. Finally, his final answer was, well, if you were just smarter, you would understand this and you would believe me. And if Dr. Mitchell can explain to me in a way that I understand about alveolar pressure, I do not think it is unreasonable to have someone who can.

LIZ KINTZING: I thought a while ago there was no direct correlation between bubbles and DCS.

NEAL POLLOCK: Bubbles do not equal DCS. We do not treat bubbles. We look for bubbles. Bubbles are an indicator of decompression stress. If you actually make the measures with the right equipment, a skilled technician, and appropriate frequency and do not have bubbles, the data suggest that you can be 95% confident you are not going to develop symptoms of decompression sickness. The data are not exhaustive, but reasonable. If you have high grade bubbles, the best evidence we have is from the aviation decompression literature. And it suggests that you have at most a 40% probability of DCS. So, while bubbles do not equate to DCS, you also should not say they are unrelated. The defeatists say, we have bubbles after every dive; why worry. That is not true. I can show you literally hundreds of clips where we have used pretty sensitive ultrasound equipment and we have not been able to identify intravascular bubbles. Are there perhaps some in the tissues? Yes. Are there perhaps some that are so small we cannot see them? Yes. But we can see with the current technology pretty well. The absence of measurable bubbles with current technology is a good indicator of decompression safety.

MARTY McCAFFERTY: Dr. Pollock, could you clarify for this audience, was this diver with high bubble grades symptomatic or not?

NEAL POLLOCK: This was an interesting case. The diver was female, and the scan was recorded 20 min post-dive. She became symptomatic, presenting with bilateral breast pain and visual floaters. She declined treatment with the comment that this happened after many of her technical dives and that the symptoms always went away. As mentioned by others, divers may be impaired. Decision-making can be terrible during acute exposure to hypercapnia or hypoxia, for example. Post-dive thinking can also be impaired by decompression sickness. In this case the individual modified her gradient factors. She dived the next morning and surfaced happily with no symptoms, but this did not last. There is a keenness in the recreational technical diving community that must be appreciated. Some of them just do not want to stop.

KARL HUGGINS: You said 80% of the subjects had post-dive bubbles?

NEAL POLLOCK: In one series we found 80% of subjects to have non-zero grades over one week of recreational-technical diving (55 divers completing 287 dives). In individual trips we have seen as many as 80% of the subjects have some left heart bubbles, but the average with this 287 dive series is on 13% of dives. We have participated in other trips where we have seen very few left heart bubbles. I do not think with the new technology we have had a trip seeing no left heart bubbles, but we certainly have some subjects who will dive all week with no bubbles evident.

KARL HUGGINS: So my question is whether these bubbles are all associated with a patent foramen ovale (PFO).

NEAL POLLOCK: We can sometimes be reasonably sure of a PFO if we see a massive flush of bubbles arriving in the right heart immediately followed by a massive number appearing in the left heart. If, on the other hand, there is a massive flush of bubbles on the right with some appearing in the left only several cycles later, it is more likely to reflect transpulmonary shunting, passage through the lungs. One of the reasons to stay away from post-dive exercise is that exercise (or bearing down as you do when performing a Valsalva maneuver), you can promote transpulmonary passage. A very interesting study demonstrated how healthy individuals shunted bubbles across the lung in rough proportion to the work intensity (Eldridge et al. 2004). So, you want to avoid post-dive exercise to reduce bubble formation and to reduce transpulmonary passage if you do have bubbles.

DAVE CONLIN: Neal, how does that decompression sickness rate for scientific diving compare with commercial diving?

NEAL POLLOCK: Commercial diving and research military diving have some extreme rates, peaking at 35/10,000, but those are almost certainly not reflective of the normal levels. The extreme estimates are pretty old data now. In any case, the numbers for scientific diving are favorable, 0.34/10,000, about one-tenth of the rates reported for other sub-communities (Dardeau et al. 2012). To be fair, it should be remembered that the high frequency of very shallow diving contributes substantially to the low rate.

DAVE CONLIN: Do you have any subjective impressions about where we stand with regard to commercial diving?

NEAL POLLOCK: One of the challenges is that you can treat on the fly with commercial diving. Commercial diving was almost certainly towards the higher end historically. I expect that it has gotten much safer but I cannot give you numbers. One of the things to remember is that the denominator data is typically poor for most of the communities. As a simple example, how many divers are there in North America? Published estimates frequently range from one million to four million. There is little hard information available on the number, let alone how active individual divers are. The data do suggest that scientific diving is one of the safest sub-communities, a record we will hopefully maintain.

ROGER MAYS: A question about ascent rates. A lot of us were certified when 60 ft (18 m) per minute was the standard. Did you guys see when everybody changed to 30 ft (9 m) per minute? Did you see any change in the data?

NEAL POLLOCK: I do not know of good data to empirically compare the safety of the two rates. The major challenge is that the rate was not the only change. The safety stop gained popularity over the same period. It likely improves your decompression safety in two ways; by reducing ascent rate in the critical shallow zone where the rate of relative pressure reduction is highest as you near the stop, and then through the stop time. So, our understanding of the impact of ascent rate changes is confounded, but to the benefit of the community. There is little doubt that slower ascents rates in the shallow zone are safer. An ascent rate study started at DAN was stopped prematurely when the 'fast' ascent rate was associated with a high rate of DCS. The fast ascent rate was 60 ft per minute.

DAVE CONLIN: I would just say for most of the people in this room the critical question is not risk tolerance. It is a programmatic or agency risk tolerance.

NEAL POLLOCK: You are right. You can substitute agency for this because you are controlling the dive. Ultimately, I am a little bit cynical. I think it is more important to educate divers than to regulate divers. A diving officer is often not around for all dives. When your back is turned, diver knowledge and buy in become critical determinants of action.

DAVE CONLIN: But those are two separate questions. Because the point is what is your institutional policy for mitigating decompression risk versus what are the individual divers choosing to do.

NEAL POLLOCK: You can substitute institutional for all of this. But I believe even as an institution you have to make sure your divers understand the risk to ensure the best compliance and readiness. Someone has mentioned that no one wants to follow a rule that is deemed unhelpful. You have to make sure that they truly understand. We do not disagree; I just think you have to hit both levels. You have to make sure your divers buy in to manage the risk.

RICHARD PYLE: Two quick clarifications. Is that mostly based on empirical data or is that mostly based on our intuition of how the processes of on-gassing and off-gassing and bubble formation happen?

NEAL POLLOCK: We can tell you from our studies that bubble formation happens and that changes in the exposure can alter the pattern of formation. We cannot tell you the mechanism of why it happens.

RICHARD PYLE: Is that outcome bubble scores?

NEAL POLLOCK: Not alone. Ours is one of the few labs that still take decompression studies to the endpoint of symptomatic DCS. We monitor and grade bubbles but we do not do anything until you get symptoms. NEDU also conducts studies to the same endpoint.

RICHARD PYLE: The second part of the question is how do you distinguish mild from non-mild exercise for decompression benefit?

NEAL POLLOCK: That is a very difficult question to answer simply but adequately. I will tell you what we use as a guideline for your light exercise, about 2 to 3 MET (metabolic equivalents). One MET equals an approximation of resting effort. So, we are talking two to three times resting level, very low intensity exercise. Most recreational divers with good neutral buoyancy skill should be averaging no more than 3-4 MET. This would be in minimal current, less than 0.5 knots, with good buoyancy control.

RICHARD PYLE: So translating that to decompressing divers, hanging on a rope dead still would be a 0 MET. Swimming mildly would be maybe 2-3 MET?

NEAL POLLOCK: Zero MET would be dead; 1 MET is the metabolic effort of rest. Hanging on the line could put you in the 1.5 MET range, depending on buoyancy control and thermal status. Relaxed swimming horizontally around that stop, or slightly negative and kicking up to maintain it could be appropriate. Keep yourself moving and warm.

RICHARD PYLE: Not swimming as hard as you can?

NEAL POLLOCK: You want to avoid high joint forces that can promote bubble formation, before, during, and after diving.

LIZ KINTZING: What are the decompression sickness rates for the 'cold-cold' and 'warm-warm' status dives? It seems like they should be equal.

NEAL POLLOCK: 'Warm-warm' allowed more bottom time at a slightly lower rate, but I do not remember all the numbers.

KARL HUGGINS: I think 'warm-warm' was 70 min, and it was up at about 18%. And cold-cold was down at 60 min because of the longer time, and that was up at about the same 22% as a 'warm-cold.'

NEAL POLLOCK: [Follow up] All dives were to 120 fsw (37 msw) with 91 min spent in ascent. 'Cold-cold' had a bottom time of 60 min with 22% (4/18) DCS. 'Warm-warm' had a bottom time of 70 min with 17% (4/24) DCS (Gerth et al. 2007).

DAVID KUSHNER: Quick question, Neal. The temperature differential, does it matter what range you are in? So if you are in relatively warm water --

NEAL POLLOCK: That is a good question. Thermal balance depends on your thermal protection for a given temperature range. You preserve a fairly narrow band for comfort. If cold you will vasoconstrict more. The greater the gradient of heat from your warm body to cooler water, the greater the stress. We can talk about priorities. Operationally, you have got to be warm enough to be able to think clearly. So you need enough insulation so you can do your job. What you need after that is challenging. I think that we have a problem, certainly in the recreational community and somewhat in science and other diving, in that comfort rules. If comfort rules, you make bad decisions. I think you need to be warm enough to be operationally effective, but you should avoid excess warming during the descent and bottom phase since it will increase your uptake. There are ways to moderate the risk of active heating garments. You could leave the system off during the first part of the dive and turn it on at the end. This still has some risk. One participant in this meeting described turning on his heating garment during the decompression stop and developing skin symptoms. He then went back to leaving the garment on the whole time. While attractive, this does create the 'warm-warm' condition, physiologically less preferable than 'cold-warm.' An alternative for more flexible systems is to leave them on at the lowest setting during the descent and bottom phase and then crank it up during the ascent and decompression phase. In this case you know the device is working and you are not drawing as much power. You will hopefully have enough for the high power setting at the end. There are a couple of things you have to think about. When you crank it up, there is a chance for skin symptoms when you heat the local tissue since you are decreasing the solubility of that tissue. Thoughtful use is important. For me, I like the passive insulation and a little bit of exercise. But if you are in-waters where either the decompression stress is very low or you need active heating to function properly, it is the right thing to use. We need to promote awareness of the potential risk, since I am not aware of any manufacturer acknowledging that they have the potential to adversely affect decompression risk.

PHIL SHORT: Just to define "crank it up," basically, going from warm to hot, a company whose equipment I use, the biggest complaint from people who buy it is even cranked up they say it is not working. They send it back. You do not switch it on like a motorcycle vest you can buy in a motorcycle shop. Suddenly you feel like you are wearing a heated blanket. There are two settings. And what it is doing is it is pulsing voltage. So on the low setting it is pulsing at a certain time and high pulsing is quicker. It is a very, very low temperature so you almost do not realize you have turned it on.

NEAL POLLOCK: Thanks for that important clarification. The biggest jumps in active heating are likely to produce the biggest stress locally.

JEFF GODFREY: I am happy to talk about my incident and what changes I made. I used the same heating vest system too, but it has an on and off switch without settings. I had been in the habit of turning it on at the beginning of the dive. Because of the information presented, I decided to leave it off during the dive and turn it on at the 20 ft (6 m) deco stop. After a dive to 240 ft (73 m) using this method I developed symptoms of skin bends on my upper arms and shoulders so I have reverted to turning on the vest at the beginning of the dive and leaving it on. I think by the time you reach the 20 ft (6m) stop you already have a fair amount of decompression stress.

NEAL POLLOCK: We are down to the art. I would be fine conceptually turning it on at the end of the compression phase since it will take a bit of time before there is any impact and inert gas uptake will decrease throughout ascent.

AUDIENCE MEMBER: Does the acclimatization you described have a turning point?

NEAL POLLOCK: That is the question. Where does it become bad? The protective effect we saw was evident because we had identical profiles (Zanchi et al. 2014). I believe that effective acclimatization can work and it did work in this study, but you have to realize that with multiple dive days could increase risk if the stress is on the higher side. So it depends on how conservative the dives are and that is affected by a host of individual differences. I do not have data to back this up now, but I believe that modest exposures favor a protective benefit while more extreme exposures could potentiate the risk. Positive acclimatization is not something you want to rely on, but it may be important to understand the nuance of decompression physiology and, in the right circumstances, it could act in your favor. As with all things, you have to be thoughtful to manage the integrated risks.

KARL HUGGINS: One question on that. How were you controlling them between the dives?

NEAL POLLOCK: They stayed with us in the lab space for two hours of post-dive monitoring. Physical activity was kept low. They went home at night with the understanding that they were supposed to avoid strenuous exercise. Ultimately, we controlled what we could but relied on their commitment to the protocol. We had 16 subjects and they all seemed to be pretty compliant.

JESSICA KELLER: Are there any plans to do additional testing on this?

NEAL POLLOCK: We would like to do more. I would like to complete an eight-day series, and then possibly with repetitive daily diving. It is hard because this is a huge commitment for the divers. We have had some discussions with NOAA folk about monitoring some of their series. It could be a good option.

DAVE KUSHNER: Do you want double reporting of diving incidents?

NEAL POLLOCK: What comes through to DAN has nothing to do with AAUS. So I would be perfectly happy with double reporting. We do not use the data statistically but descriptively for education purposes. Some of our most useful cases are the few that are very well documented. Please share to help others.

Incident reporting - http://DAN.org/IncidentReport

AUDIENCE MEMBER: Do you work with the training agencies to make them aware of the incident reports?

NEAL POLLOCK: The training agencies all know that we produce annual and special reports. They are free and available to all for electronic download.

MAURITIUS BELL: I know they are aware of this, but have you approached them about putting it into the basic course? The example I use is what you guys are doing comes from the aviation community, but as flight instructors we teach all basic students in the US all flight instructors explain to them the importance of a NASA report.

NEAL POLLOCK: DAN makes insurance available to students who register or are registered while they are being trained. That is intended to increase their awareness. How much the agencies share or promote is up to them. We certainly have ongoing communications.

SIMON TALBOT: The Australian Diver Accreditation that we teach our scientific courses through requires incident reports for anything that occurred. And they release the data on three-monthly basis pretty much, but sanitized. That would be a fantastic thing for the AAUS to put together.

NEAL POLLOCK: Absolutely, but you also have to remember that AAUS is almost wholly a volunteer organization. DAN is not and it is tough for us. I will tell you what we are trying to do with these online systems. We are trying to select vignettes of high educational value and put them on the website. It is a great idea but in practice it takes a substantial commitment.

RICHARD PYLE: Comment and question. Several people in this room have teased me about the amount of thermal protection I wear below the thermocline on deep dives and the fact that I continuously swim laps around them during decompression. Perhaps these people, and they know who they are, will not tease me so much in the future. The question that brings it back to rebreathers, is that part of the reason I do these continuous mild swims on decompression is that I subjectively feel warmer. And a big part of that is not only the energy I am burning muscularly, but also the CO_2 I am producing that is generating exothermic reaction in the absorbent, which makes the gas that I am breathing warmer. My question is, does that addition of heat contribute in any way to the cold-warm benefit or are we only really talking about water temperature?

NEAL POLLOCK: Thermal heating has impact however it is achieved. Your physical work warms you in two ways as you described. Physical effort is not desirable during the inert gas uptake phase of the dive, but can be very beneficial during the elimination phase as long as the intensity is not sufficient to promote bubble formation. There is a dualism to exercise; a little can be good, but too much or the wrong type can be problematic.

RICHARD PYLE: The reason I ask is that swimming, if the water temperature is the same, moving through the water as opposed to hanging on the rope, you have a "windchill" factor and you actually lose heat at the skin more rapidly because you are moving through the water. But, in terms of energy, I am still gaining more in the body for it. I did not know whether this 'cold-warm' effect had more to do with your peripheral temperature versus your core temperature.

NEAL POLLOCK: The core temperature is probably fairly stable. It is the peripheral temperature that can be more variable. You can cool the peripheral tissues externally by exposure to cold, an effect that would be augmented by minimal exercise levels. Your convective losses could be substantial if you were completely unprotected, depending on the water conditions, but you would be warming endogenously through the exercise and the respired heat from the active scrubber. The benefits would outweigh the cost in conditions with modest environmental cold stress, which is likely what you would have if you were able to tolerate the conditions for a normal dive.

SIMON MITCHELL: Neal, can I just add a comment to that. I totally agree with it, but remember, Rich, that the benefits of temperature and mild exercise are both working through the same mechanism, which is improvement of perfusion of the tissues. The fact that exercise creates this convective loss because you are moving through the water I think is kind of irrelevant.

RICHARD PYLE: You do not think it is additive. It is just basically the same thing.

SIMON MITCHELL: You are perfusing your tissues better. That is what you are trying to do. Temperature and mild exercise helps with that.

RICHARD PYLE: There is also the double benefit of being cooler and less exercise when you are on the bottom.

SIMON MITCHELL: And less perfusion.

RICHARD PYLE: Exactly.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

Decompression Science: Critical Gas Exchange

Simon J. Mitchell
Department of Anaesthesiology, University of Auckland, Auckland, New Zealand
sj.mitchell@auckland.ac.nz

Abstract

There are two broad classes of decompression algorithm: gas content models and bubble models. Based on their compelling theoretical attraction bubble models enjoyed a long period of popularity among technical divers in the early 2000s, largely in the absence of supportive data. More recently several comparative studies have demonstrated increased numbers of venous gas emboli after decompression dives planned using bubble models, and one study demonstrated a greater incidence of decompression sickness (DCS). It seems that protection of faster tissues early in the ascent by imposing deeper decompression stops (a key characteristic of the bubble model approach) is not as effective at controlling bubble formation as hypothesized. Indeed, it may fail because of continued uptake of inert gas by slower tissues during deep stops, causing these tissues to subsequently become more supersaturated later in the ascent. There is a general sense that bubble models may over-emphasize deep stops, and divers using the gradient factor approach to manipulating a gas content model may choose to de-emphasize deep stops. The optimal approach to decompression from deep bounce dives is, however, unknown. Another area of controversy is whether inert gas switches (from helium to nitrogen-based diluent) should be employed during decompression from deep rebreather dives. The efficacy of such switches in accelerating decompression has recently been questioned, and given the potential for such switches to (albeit rarely) contribute to inner ear DCS, and the lack of a financial imperative to save helium in a rebreather system, opinion seems to be swinging toward staying on helium based diluent throughout decompression in rebreather diving.

Keywords: diving, rebreather, decompression, deep stops, bubble model, gas content model

Introduction

Few issues in diving are as contentious and vexed as the debate around what constitutes the optimal approach to decompression.

This paper is a brief and superficial summary of current debate about the relative merits of decompression algorithms based on gas content models and bubble models. This is a simple account that concentrates on the basic philosophical differences between these different approaches to decompression and avoids discussion of the specific mathematics and modelling techniques. Basic (Doolette and Mitchell 2013) and more advanced (Doolette and Mitchell 2011) accounts of these latter subjects are available. The paper also briefly addresses the controversy around whether to perform diluent gas switches during decompression from deep bounce dives using rebreathers.

The Process of Decompression, and Decompression Modelling

During the descent and bottom phases of a compressed gas dive, the pressure of inspired inert gas (e.g., nitrogen in air diving) is increased, and this gas is absorbed into blood and then carried to tissues. Over time, the tissue inert gas pressure trends toward equilibration with the inspired pressure as gas diffuses from blood into the tissue. The rate at which equilibration occurs is faster for some tissues than others;

equilibration tends to occur more quickly in tissues with high blood flow and/or low solubility for the inert gas, and vice versa. Rapidly equilibrating tissues are often referred to as "fast tissues" and tissues which equilibrate more slowly are referred to as "slow tissues." If there comes a point where tissue inert gas pressure does equilibrate with the inspired pressure the tissue is said to be "saturated."

As ambient pressure falls during ascent the inspired inert gas pressure also falls and, once inspired gas pressure falls below the pressure of gas dissolved in a tissue, a pressure gradient becomes established for inert gas to move out of tissues into the blood, and thence to be carried to the lungs and exhaled. However, depending on the rate of ascent and whether the tissue is 'fast' or 'slow' there will likely come a point during the ascent where the sum of dissolved gas pressures in the tissue exceeds the ambient pressure. At this point the tissue is said to be "supersaturated." This is significant because once supersaturation occurs bubbles may form in the tissues themselves or in the blood passing through the tissue microcirculation. The latter bubbles subsequently pass into the veins where they can be detected using either Doppler technology or echocardiographic imaging when they arrive in the right heart. Depending on their size, number and distribution (and other factors), formation of these bubbles may result in the development of symptoms of decompression sickness (DCS).

Not surprisingly (given the preceding discussion) strategies to prevent DCS focus substantially on controlling tissue inert gas supersaturation. Implicit in this approach is the mathematical approximation of inert gas uptake and elimination by a range of hypothetical tissues during a dive, and the tracking of inert gas pressures in those tissues relative to the ambient pressure particularly during the ascent. Using the relevant calculations, control of tissue supersaturation can then be achieved by slowing the ascent rate or imposing stops in the ascent to allow time for inert gas to diffuse out of tissue before supersaturation exceeds some predetermined acceptable threshold. The biggest difference between the approaches to decompression planning discussed below is their respective "views" on acceptable degrees of supersaturation in the various tissues over the course of the ascent.

Gas content models

The so-called gas content models, such as those proposed by Haldane and later by Buhlmann, were the first widely used and largely successful decompression strategies. The underlying decompression philosophy was an aim to establish the largest tissue supersaturation that could be tolerated without producing DCS because this would maximize the gradient for tissue outgassing and therefore (in theory) maximize inert gas elimination. In this approach, a series of supersaturation limits were calculated based initially on animal experiments by Haldane, but later modified many times based on a mix of theoretical and empirical adjustments. Arguably the most famous of these sets of limits were the ZH-L16 ascent rules for 16 hypothetical tissues promulgated by AA Buhlmann. These have formed the basis for many decompression strategies still in use today.

In decompression diving, it is an inevitable result of the underlying philosophy (see above) that gas content models allow an initially large excursion toward the surface before imposing the first decompression stop. This frequently results in relatively large supersaturations in faster tissues early in the ascent because these tissues have often equilibrated (or nearly so) with the pressure of inspired inert gas during the period at the bottom. However, these supersaturations are relatively short-lived because the fast tissues eliminate inert gas quickly. This characteristic of gas content models becomes relevant as this narrative further unfolds.

Since gas content models were the archetypal approach to decompression there was little else to compare them with in the early days. Most evolution of the approach involved tinkering with the supersaturation thresholds, but the underlying philosophy of maximizing supersaturation without producing symptoms persisted. It was, of course, clear from the start that these approaches to decompression were not invariably successful. Cases of DCS still occurred even when divers adhered rigidly to the decompression procedure prescribed by their decompression table. Moreover, the advent of Doppler technology demonstrated that bubbles formed in tissue capillary beds appeared in the venous blood very commonly after surfacing from dives. Although it was clear that this could be tolerated in most cases (because the divers did not have symptoms of DCS), it was a confronting finding for many who had assumed that adhering to the supersaturation thresholds prescribed by gas content models actually prevented bubble formation. The combination of the frequent formation of bubbles and sporadic occurrence of DCS despite adherence to decompression procedures prescribed by bubble models provided fertile ground for the emergence of alternative philosophical approaches to decompression.

Bubble models

The most important of these alternative philosophies is the so-called bubble model approach to decompression. The fundamental philosophical difference to a gas content model is the belief that the initial large ascents permitted by the latter (which, as described above, result in significant supersaturation of fast tissues) are a strategic error which initiate the formation of bubbles that may later go on to produce symptoms. The bubble model approach holds that smaller supersaturations during the ascent will permit control of bubble formation within predictable parameters of number and size, and that this will reduce risk of DCS. The mathematical approach employed in bubble models is described elsewhere (Doolette and Mitchell 2011; 2013) and will not be explored here. However, it should be obvious that in order to impose smaller supersaturations during ascent a decompression algorithm will impose decompression stops earlier in the ascent to reduce supersaturation in the faster tissues. This approach has resulted in bubble model decompressions becoming synonymous with the term "deep stops."

The obvious theoretical attraction of the bubble model approach to decompression saw these models become very popular if not ubiquitous among technical divers in the early 1990s. Several proprietary bubble models (the Variable Permeability Model – VPM; and the Reduced Gradient Bubble Model – RGBM) emerged and were adapted into decompression computers for both scuba air and technical divers. Such was the faith in the "bubble control concept" that some early bubble model decompressions were conspicuously shorter than gas content model ascents despite the imposition of deeper stops. The underlying assumption was that prevention of initiation of bubble formation early in the ascent allowed shorter stops later in the ascent. There was some empirical reversal of this assumption (and adjustment of bubble model algorithms) in response to DCS cases, but the perception that bubble model decompressions were safer and more efficient nevertheless persisted.

It is relevant to mention that even among divers who continued to employ gas content model supersaturation limits in their dive planning there was an almost ubiquitous trend to using methods that made the prescribed ascents look more like bubble model decompressions. The use of the so-called "gradient factors" method is the most conspicuous example of this. In this method, the diver chooses a fraction of the allowed Buhlmann supersaturation limits that will be tolerated early in the ascent and at the point of surfacing. The diver can choose fractions that are less than or that exceed the Buhlmann limits, but arguably the most common application during the period of strong belief in bubble models has been to use the gradient factor method to emphasize deep stops in the decompression profile. If, for example, the diver accepts only 20% of the allowable Buhlmann limit early, the ascent will proceed until the most supersaturated tissue reaches 20% of the allowable supersaturation and a decompression stop will be undertaken at that depth. It should be obvious that this stop will occur at a deeper depth than had the diver accepted 100% of the normal Buhlmann supersaturation limit, and this approach therefore results in deeper stops as is the case with bubble models (although clearly the underlying mathematics are very different). As mentioned, the diver also chooses a fraction of the allowable Buhlmann supersaturation that will be tolerated at the point of surfacing. If the diver chooses a fraction lower than 100%, then the final shallow decompression stops will be longer in order to allow the slower tissues to eliminate more inert gas than would normally be required by Buhlmann prior to surfacing. The algorithm interpolates a line between the two chosen "gradient factors" which essentially specifies a re-defined range of allowable fractions of the Buhlmann limits that will be followed throughout the ascent.

Human Data

It is fascinating to reflect on the fact that the widespread perception of bubble model superiority for decompression diving was unsupported by any data from human studies (or animal studies for that matter). Indeed, the mass gravitation to the use of bubble model approaches to decompression among technical divers was substantially based on theoretic attraction and word-of-mouth promotion. The fact that many thousands of technical dives are undertaken using bubble models is often mistaken for or indeed, incorrectly portrayed as evidence of superiority of the models. In fact, while such observations demonstrate that bubble model decompressions do work in the majority of dives, they do not constitute evidence of superiority in comparison to other approaches to decompression.

On that background it is equally fascinating that the small number of relevant human studies that have emerged in recent times have challenged the bubble model approach. The first relevant study was published by Blatteau et al. (2005) who compared venous bubble grades in divers following decompressions (from 165-200 ft [50-60 m] dives) performed according to protocols prescribed by their standard gas content model or several experimental "deep stops" models. They found higher bubble grades following several of the deep stops decompression profiles. In a more recent study of technical diving decompressions using a bubble model, the authors recorded very high venous bubble grades following almost every dive (Ljubkovic et al. 2010). This was not a comparative study but the finding of consistently high bubble grades after decompressions prescribed by a model whose stated goal is to control bubble formation was surprising and somewhat ironic. While these studies are interesting, the relevant outcome measure was venous bubble grades as opposed to clinical DCS, so the conclusions that can be drawn are limited.

The most important relevant human data comes from the US Navy Experimental Diving Unit (Doolette et al. 2011). At the height of bubble model popularity among technical divers in the mid to late 2000s the USN were contemplating shifting the emphasis of their dive planning tools from gas content models to bubble models. They designed a trial designed to isolate the effect of distribution of stop time (either emphasizing deep stops or shallow stops) in dives that were otherwise identical (same depth and bottom time, and length of decompression). The dives were all air dives to 170 fsw (52 msw) for 30 min bottom time, conducted in water at 86°F (30°C) with no thermal protection and with the divers exercising at 115 watts during the bottom time. Air was breathed throughout the decompression. The decompression profiles were generated by a gas content model (VVal-18, shallow stops) and a bubble model (BVM-3, deep stops). These models are USN-designed algorithms whose details are beyond the scope of this discussion, but both produce decompression profiles with characteristics that are typical of the underlying decompression gas content and bubble model philosophies respectively. Although an uncommon approach in decompression diving, air was used throughout the decompression in order to prolong the decompression and thereby to help unmask any significant influence of redistribution of stop time on outcomes. The profiles are shown in Figure 1. The primary outcome was the incidence of DCS diagnosed by the duty diving medical officer following the dives. Venous bubble grades were also measured after diving as a secondary outcome measure.

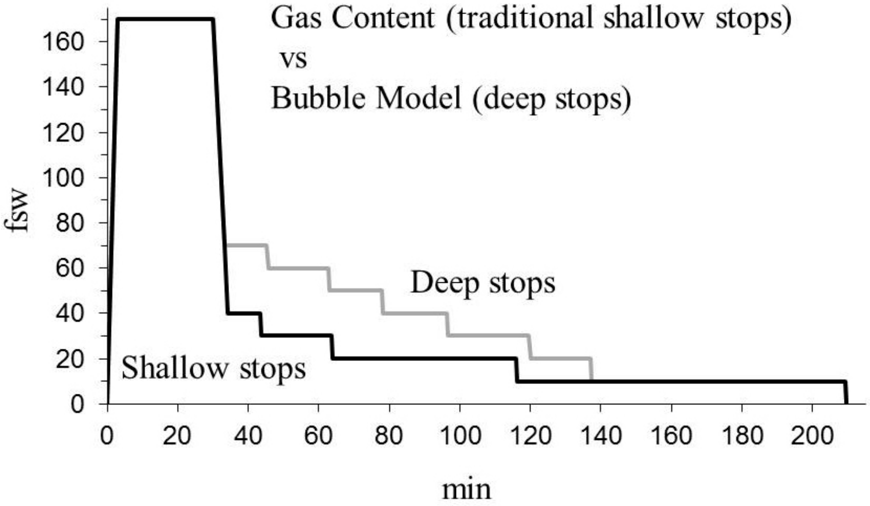


Figure 1. Dive profiles in the NEDU deep stops study.

In accordance with the approved protocol the study was stopped when the incidence of DCS became significantly different between the two groups on a sequential analysis. At that point there had been three cases of DCS in 192 dives (1.6%) on the shallow stops profile and 10 cases in 198 dives (5.1%) on the deep stops profile. The secondary analysis also showed that the deep stops profile was associated with a higher proportion of divers exhibiting high venous bubble grades. On this basis, the USN has declined to widely adopt bubble model decompression for its own purposes.

The result begs the obvious question "why did the deep stops fail"? Analyses of the supersaturation (expressed as an integral of supersaturation magnitude and time) across the range of hypothetical tissues (from fast to slow) at all stages of the ascent demonstrate that the NEDU deep stops profile did result in less supersaturation of the fast tissues early, which is the property of a bubble model hypothesized to control bubble formation. But the analyses also reveal that this comes at the price of more supersaturation of the slow tissues later in the ascent because of continued inert gas uptake into these tissues during the deeper stops. The poorer clinical outcomes and higher bubble counts in the deep stops arm of the study suggest that the assumption that reducing supersaturation in fast tissues early in an ascent will control bubble formation and result in less DCS may be flawed; indeed, the study results indicate that supersaturation of slower tissues later in the ascent is a more important determinant of bubble formation and risk of DCS.

The NEDU deep stops study has generated an immense amount of debate within the technical diving community. The most common criticism centers around the superficial observation that the NEDU deep stops profile "does not look like" profiles that would be generated by bubble models (such as VPM) typically used by technical divers. Specifically, a typical VPM profile would have been shorter, and would have included a very short series of even deeper stops. However, in reality, the NEDU deep stops profile is not significantly different from a VPM profile where the latter model is applied with sufficient conservatism to produce a profile of identical length to the NEDU dives. Moreover, this argument ignores the fact that the apparently disadvantageous supersaturation pattern (decreased supersaturation in fast tissues early and increased supersaturation of slow tissues later) is highly likely to be replicated in any dive where a finite amount of decompression stop time is distributed deeper rather than shallower. Indeed, analysis of decompression profiles for real world technical rebreather dives prescribed by commonly used bubble and gas content models reveals the same apparently disadvantageous pattern of supersaturation distribution repeating itself, even when bubble model profiles are compared to gas content models modified by gradient factors to introduce some deep stop characteristics. Thus on the basis of currently available data and contrary to previous widely held belief, there is no reason to believe that bubble model/deep stop decompression is more efficient than decompression prescribed by a gas content model when dives of equal length are compared. Indeed, one would be compelled to draw the opposite conclusion.

Unfortunately, the NEDU study does not define optimal decompression and nor does it provide a basis for definitive advice to technical divers on this issue. Perhaps the best that can be said is that the concept of using bubble model decompressions to improve decompression efficiency has been 'oversold' to the technical diving community and that the current best evidence suggests that approaches which de-emphasize deep stops to some poorly defined extent are preferable. Many technical divers who use the gradient factor approach to decompression planning (see earlier) are responding to this scenario by increasing the 'gradient factor low' and are thus accepting a higher fraction of the allowable Buhlmann supersaturation limit in determining the depth of their first decompression stop. There is, however, no objective basis for a recommendation on how far such "backing-off" from deep stops should go. The knowledge we seek on "optimal decompression" remains an elusive goal.

Diluent Switches During Decompression from Rebreather Dives

Another decompression controversy independent of the above discussion about decompression models but relevant to scientific dives with rebreathers relates to the use of gas switches during decompression from deep mixed gas dives. Specifically, in open-circuit diving it has been common practice to switch from trimix to air and/or progressively richer nitrox mixes during decompression, and ultimately, to breathe 100% oxygen during the final shallow stop. There are several goals underpinning this practice. First, the elimination of helium from the breathing mix saves on the cost of this expensive gas. Second, the progressive increase in the inspired fraction of oxygen hastens the elimination of all inert gases. Third, it is perceived that substituting nitrogen for helium in the inspired gas will (independent of increasing the inspired oxygen fraction) accelerate elimination of helium because helium will diffuse out of tissues into blood faster than the nitrogen will diffuse from the blood into tissues. This favorable "counterdiffusion" process would have the effect of causing at least a transient enhancement of gas elimination from tissues. The practice of gas switching has also found its way into rebreather diving in the form of diluent switches during decompression (for example, a switch from trimix diluent to air diluent at an appropriate depth).

The first two of the above goals are clearly legitimate. The third is more controversial. It has long been assumed, mainly on theoretical grounds, that helium to nitrogen switches during decompression will reduce supersaturation in most tissues (Lambertsen and Idicula 1975). The related controversy arises in part from the long standing recognition that such switches may occasionally be associated with the onset of inner ear DCS. Because of its unique anatomy, the inner ear is perhaps the only organ in which a helium to nitrogen switch can produce an unfavorable gas counterdiffusion process. The mechanism was recently summarized by Mitchell and Doolette (2015) as follows:

"The perilymph and endolymph are non-perfused compartments that take up and eliminate inert gas through the perfused membranous labyrinth. After a period of heliox breathing, the perilymph, in particular, accumulates a substantial reservoir of helium. Following a switch to nitrox breathing, owing to a higher diffusivity of helium than of nitrogen, diffusion of helium from the perilymph and endolymph to the membranous labyrinth exceeds the diffusion of nitrogen in the opposite direction. At the same time, owing to higher solubility of nitrogen than of helium in blood, delivery of nitrogen to the membranous labyrinth in the arterial blood exceeds the removal of helium in the venous outflow. Together these could cause a transient supersaturation of the membranous labyrinth without decompression."

The risk of such events is low (Doolette and Gerth 2014) but it has nevertheless caught the attention of the technical diving world. In addition, there is some doubt over whether gas switches really do accelerate inert gas elimination in tissues other than the inner ear and therefore over whether there is any advantage in doing them from a decompression point of view. In a recent study, Doolette et al. (2015) were unable to demonstrate any difference in helium and nitrogen kinetics in brain or skeletal muscle, and this could be interpreted to imply that a gas switch would not of itself materially alter inert gas pressures in these tissues at least.

It is therefore concluded that while gas switches will undoubtedly continue to be employed by open-circuit divers to save on the huge cost of helium, there is little compelling reason (and perhaps some small risk) in doing them during rebreather dives where very little helium is used, even if a helium diluent is employed throughout the dive.

References

Blatteau J-E, Hugon M, Gardette B, Sainty J-M, Galland F-M. Bubble incidence after staged decompression from 50 or 60 m: effect of adding deep stops. Aviat Space Environ Med. 2005; 76: 490-2.

Doolette DJ, Gerth WA, Gault K. Redistribution of decompression stop time from shallow to deep stops increases incidence of decompression sickness in air decompression dives. Panama City, FLA: Naval Experimental Diving Unit TR 11-06; 2011, 20pp.

Doolette DJ, Mitchell SJ. Hyperbaric conditions. Comprehensive Physiol. 2011; 1: 163-201.

Doolette DJ, Mitchell SJ**.** Recreational technical diving part 2. Decompression from deep technical dives. Diving Hyperb Med. 2013; 43: 96-104.

Doolette DJ, Gerth WA. Safe inner ear gas tensions for switch from helium to air breathing during decompression. Panama City, FLA: Naval Experimental Diving Unit TR 12-04; 2013, 14pp.

Doolette DJ, Upton RN, Grant C. Altering blood flow does not reveal differences between nitrogen and helium kinetics in brain or in skeletal muscle in sheep. J Appl Physiol. 2015; 118: 586-94.

Lambertsen CJ, Idicula J. A new gas lesion syndrome in man, induced by "isobaric gas counterdiffusion". J Appl Physiol. 1975; 39: 434-43.

Ljubkovic M, Marinovic J, Obad A, Breskovic T, Gaustad SE, Dujic Z. High incidence of venous and arterial gas emboli at rest after trimix diving without protocol violations. J Appl Physiol. 2010; 109: 1670-4.

Mitchell SJ, Doolette DJ. Pathophysiology of inner ear decompression sickness: potential role of the persistent foramen ovale. Diving Hyperb Med, 2015; 45: 105-10.

QUESTIONS AND DISCUSSION

LIZ KINTZING: How did Buhlmann come up with his supersaturation limit?

SIMON MITCHELL: Initially with mathematics. Then by testing and empirical modification after use in the field.

DAVE CONLIN: When you are moving on these shallower stops with supersaturated slow tissues your individual pressure gradients between sequential stops is much greater so one would expect greater bubble formation as a consequence of that too; is that correct?

SIMON MITCHELL: These are actually smaller supersaturations. This scale is actually smaller than the other one. It is important to integrate supersaturation with time because when fast tissue become supersaturated they do not stay supersaturated for long. But with slower tissues you can see you have got big integrals of time and supersaturation. The area under the curve is much greater, which is part of the point you are getting at.

SIMON TALBOT: It is the tissue perfusion relationship, the off-gassing much faster in the fast tissues.

SIMON MITCHELL: Correct. That is why they are fast tissues; because they perfuse better. Fast tissues are fast tissues mainly because of perfusion. There are other factors like the solubility of the gas in the tissue compared to the solubility in blood, but they are fast tissues mainly because they get more blood flow.

BRETT SEYMOUR: On the flip side, how can people look at a study like this and say that it was flawed? You mentioned earlier the people who do not prescribe to it do not understand it.

SIMON MITCHELL: I am coming to that.

JEFF GODFREY: Can you see if there was a difference in the ratio between type 1 and type 2 DCS?

SIMON MITCHELL: Good question. The answer is there were not enough cases to be sure, but, no. Both profiles resulted in a mix of cases. And so what you are thinking is that with greater supersaturation of the slow tissues you might have got more type 1. There were type 2 in both of these definitely, and in roughly the same proportions, but the numbers were very small.

DAVE PENCE: Has anyone looked at what further decompression would have been required to protect both the slow and the fast tissues?

SIMON MITCHELL: No, but you could do that. You could play around with this and come up with a better profile. But, I guess what David would say if he was here is, well, actually, as a military unit, we are actually really happy with the results of the shallow stops profile. We ran hard-working dives on air with no oxygen acceleration of decompression, with thermal stress and we got three cases of DCS in 200 dives. That is pretty good. And I think, actually, it probably is. These were very provocative dives. Do not make any mistake about that. It was a provocative profile.

KARL HUGGINS: So the standard profile was derived from the VVAL-18?

SIMON MITCHELL: Yes.

KARL HUGGINS: So if you ran through the VVAL-18 the initial deeper stops before you reached the ceiling, did anyone look at how much additional decompression would be required?

SIMON MITCHELL: No, they did not. One of the questions that often arises is "would it be better if you did deep stops and extended your shallow stops in order to compensate for those deep stops"? You could do that, but based on these data, I do not think that there is any advantage in it. There is no evidence of an advantage from protecting the fast tissues early. It makes intuitive sense, but in practice, it is not being borne out. But that is part of the reason I am saying these are incomplete data. That work could be done.

DAVE PENCE: As a guy who may be doing a provocative profile in a tribal village in New Guinea with no chamber anywhere near, three out of 200 dives is not necessarily a happy outcome. So, again, is there a way to use the dissolved gas models and do the deeper stops and simply suffer the extended decompression that would be even more protective?

SIMON MITCHELL: Again, I think that what we are seeing here is that there is no evidence for protection from deep stops. What I would do in that situation is just extend my shallow stops on oxygen. Can we leave discussion of optimal decompression until the end because some of these are things that I am going to put some perspective on?

RICHARD PYLE: I have a lot I would like to comment on related to all of this, but I think it makes sense to let you finish and then we can come back to the conversation.

SIMON MITCHELL: We are well aware of your leadership role in the deep stops revolution. You are a scientist, Richard. It is evidence, data.

RICHARD PYLE: That is one of the words I want to quibble with you on, but go ahead.

JEFF BOZANIC: Just trying to understand what you are presenting with the models here. Would the gradient factor selection vary based on the dive profile in terms of depth and times? In other words, you have presented a gradient factor here of 40/74 as an example to give us a set of curves that look similar to the shallow NEDU studies. From a practical standpoint, would you vary gradient factors based on the dive profile you are looking at to achieve similar results? Or can you select a similar gradient factor that would be generally applicable to a broad range of dives?

SIMON MITCHELL: More the latter than the former. Because the beauty, if you will, of gradient factors is that by choosing your gradient factor low, you can manipulate the emphasis that your decompression places on deep stops. If you choose 10, it will do lots of deep stops. It will look just like a bubble model.

JEFF BOZANIC: It seems like you would want to choose a gradient factor of 70.

SIMON MITCHELL: That is the problem. We do not know what optimal decompression is. We think we know what it is not, but we do not know what it is. And natural caution would suggest, given that lots of people are religiously adhering to a deep stop approach, backing off from deep stops to some poorly-defined extent is probably a good idea. But how far you should back off is unclear. We do not know where the optimal is.

JESSICA KELLER: So when you were at Bikini and you are using a 40 or 50 low gradient factor, how different is your profile time-wise compared to the other people who are using 50?

SIMON MITCHELL: It did not make a lot of difference at Bikini, I have to say. You start to see the differences, bigger differences, in deeper, longer dives. We were diving mainly to 40-50 m (130-165 ft). There is a little bit of a difference. And we had one guy who was doing ratio deco. I have never seen anything quite like it. The Saratoga flight deck is at 23 m (75 ft). His first stop seemed about 1.5 m (5 ft) above the flight deck. He would just hover there. You might as well just continue diving. It was strange. And he was the only guy who got bent, I might add.

PHIL SHORT: My apologies to Rich, but what are your thoughts on instead of a bubble model that is putting deep stops in, putting Pyle stops in?

RICHARD PYLE: First of all, I curse on you for mentioning Pyle stops. I hate that term. Can I take a moment here?

SIMON MITCHELL: I am going to say one thing before you do. "Pyle stops" are a different thing to a bubble model.

RICHARD PYLE: That is what I want to get to. First of all, excellent visual representations. I think your explanation of the intermediate and fast tissues was the best I have seen shown. We thought through all of this 15 years ago when we were working on this. And I have never seen it visually represented. That is really good.

SIMON MITCHELL: There is something bad coming here.

RICHARD PYLE: No. I actually want to say I agree with almost everything. The first quibble I have is what Phil was just alluding to. This sort of equation, equality of bubble models in deep stops. And those, having been involved in this, are very, very different things. You used deep stops, but really what you were talking about was bubble models. So whenever you said X about deep stops -- let me just clarify the difference between the two. Bubble models are theoretical, conceptual, mathematical representations of what ought to be; whereas, deep stops emerged empirically from what people actually did. And the fundamental difference is what Karl and Dave were alluding to. Deep stops are an ad hoc addition to an ascent profile, which were actually modeled after shallow water safety stops. If you think of your ceiling as effectively going straight to the surface without a safety stop with a fully saturated dive, the idea of a deep stop was to add, essentially, I call them deep safety stops. Will Smith has called them Pyle stops, and I curse him, even though he is dead, for it. In any case, the important distinction is that the way we used to calculate them with desktop software and currently do them with real-time decompression computing is that they do not terminate the dive at the same time. They actually end up extending the total duration of the time. So the question is are you getting the benefit of them because you are doing an extra hour and it does increase the --

SIMON MITCHELL: We do not know --

RICHARD PYLE: Forget the benefit.

SIMON MITCHELL: Let us not assume.

RICHARD PYLE: Let us assume there is no benefit. But let us say that even if there were a benefit, you still would not know if that benefit was a consequence of the initial deep stops or a consequence of the long stops. It is a very complicated thing to tease apart. The main point I wanted to make is to distinguish the terminology. What I believe people who use the term "deep stops" to mean, it is the bubble model people who conflated them. Because they say, our models have deep stops; therefore, deep stops equal bubble models. I do not buy it, and David Yount was a dear friend of mine. I have never used a bubble model. I would never use a bubble model. Whenever you hear me talk about deep stops, I just wanted to clarify that distinction.

SIMON MITCHELL: I have no objection to anything you have just said. Nobody has addressed your methods.

RICHARD PYLE: Right, and that brings me to the second point, and that is my slight quibble with the difference between the word "data" and the word "evidence." Data is basically a subset of evidence in the broader scheme of things. And I agree with you that there is absolutely no data to support my method or any other ad hoc deep stop method. What we have now is data to show that a bubble model approach to things may be inferior in some cases. You had said on one of your earlier slides we may have some data against deep stops. We do not. We have no data against deep stops.

SIMON MITCHELL: That's your definition of deep stops. Just remember how the technical diving community uses that term which is usually in relation to bubble models.

RICHARD PYLE: I have not been paying attention to what the community is doing. I only know what I do. I wanted to sort of clarify that there is really no data. The NEDU study was beautiful and elegant and I talked to Wayne Gerth about this quite a bit right when he published it, and he and I both agreed that that is a beautiful test of the, sort of, bubble model approach which gives you the shape of the profile. But we both agree that it is not a test for what, at least at the time, which was 10 years ago, most technical divers were doing. It was an air profile that had big, long intermediate stops.

SIMON MITCHELL: But the patterns are the same.

RICHARD PYLE: No, they are not, actually.

SIMON MITCHELL: Yes, they are.

RICHARD PYLE: I have graphs that shows they are the same. I can show you that when you add the deep stops the way you add a two-minute here, a two-minute here, and pretty soon you are caught up in your ceiling, it is very different. If you plot the area between the two curves of the decompression profile, that area of discrepancy is much smaller with a deep stop approach than it is with the approach that Wayne used.

SIMON MITCHELL: By deep stop approach, you mean your approach? Sure.

RICHARD PYLE: That is my point. Maybe the Internet crowd that I have not been paying attention to has been rebranding the term deep stop.

SIMON MITCHELL: They are, I am afraid.

RICHARD PYLE: Then in that case we have a terminology complication.

SIMON MITCHELL: That is right. We do.

RICHARD PYLE: Maybe for clarity of conversation for at least this audience, it would be helpful --

SIMON MITCHELL: Pyle stops.

RICHARD PYLE: Anyway, I just wanted to make it clear that I agree with almost everything you say. I do not like bubble models for the reasons that you came up with. But I wanted the room to understand that when they hear me talking about deep stops, I am talking about something that is fundamentally different from what apparently the Internet community is talking about.

SIMON MITCHELL: I am not going to challenge any of that. It is fine. It is a different thing. It is not as widespread in the community as it used to be. Thank you, Rich.

JOHN BRIGHT: Maybe an addendum or a corollary to the third question there, what are the implications for bailout gas mix planning if the resulting switch from a helium-rich to a helium-poor mix could manifest a bubble in the inner ear.

SIMON MITCHELL: That is a really good question. Off the top of my head I would say that when you are in a bailout situation, you would accept a small risk of an adverse outcome if logistically it would be hard to carry the optimal form of bailout.

JOHN BRIGHT: Hundreds of cubic feet?

SIMON MITCHELL: Yes, exactly, of a particular gas just because you are worried about isobaric counterdiffusion. I am not sure that the risk/benefit equation would favor doing that.

JEFF BOZANIC: A question that comes to my mind in looking at your second point, gradient factors are used, what should we use. In the absence of other factors, environmental or physiological, what kind of a safety stop, and I am calling it a safety stop on purpose, should we be adding to the mandatory decompression stops that the model called for in order to provide a buffer?

SIMON MITCHELL: In other words, should we all be doing what Richard does?

JEFF BOZANIC: Essentially.

RICHARD PYLE: Not quite. How much should we not run to our ceilings.

JEFF BOZANIC: In other words, I run to my ceiling. I am done with my deco. My computer says I am clear. I am warm. I am comfortable. Nobody is panicking on the boat. Just as a buffer because there is no other factors demanding that I get out of the water right now.

SIMON MITCHELL: It is something a lot of divers do. One of the points I would make is that in using gradient factors and, for example, in choosing a high gradient factor of 70, you are already imposing quite a lot of buffer on there. You could say, well, I will routinely choose 65. Or you could leave at this time at 70 and make a discretionary decision.

JEFF BOZANIC: My point is that you do not want to violate a model when you are on decompression dives. You are better off to choose 80, but then add to it because there are times where you need to get out of the water sooner.

SIMON MITCHELL: That is a fair comment and a good question.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

Oxygen – Best Practices for Scientific Rebreather Diving Operations

Jeff M. Godfrey
University of Connecticut, Marine Sciences and Technology Center, 1080 Shennecossett Road,
Groton, CT 06340, USA

Abstract

The use of high pressure oxygen and oxygen mixtures is commonplace in scientific diving. Good risk management practice requires that divers understand the regulatory requirements and community standards for the use of oxygen. In addition, divers should have a basic understanding of oxygen system design, material compatibility, and oxygen cleaning. Scientific diving programs that service oxygen equipment should have a documented cleaning standard and should maintain good records of equipment maintenance and cleaning. Dive lockers that have oxygen fill stations and/or mixed gas blending stations should have operational standards. Due to changes in regulations and community standards, the 40% oxygen threshold that has been used for determining when diving equipment should be oxygen clean may not be best practice. The scientific diving community should review the 40% rule to determine if a different standard should be implemented.

Keywords: oxygen, rebreather, regulation, standards, cleaning, maintenance

Introduction

Rebreather diving requires the use of high pressure oxygen and oxygen mixtures. Safe handling is a critical aspect of operations utilizing advanced diving modes. An unpublished survey distributed to attendees prior to this workshop on scientific diving with rebreathers identified three oxygen fires in the scientific diving community. Two were rebreather fires that were believed to have started in the oxygen gauge hose when the cylinders were opened. The third was a cylinder fire that started in the neck and valve area of a 40 ft^3 aluminum cylinder during trans-filling. To prevent loss of life, catastrophic injury and damage to equipment and facilities, persons in charge of rebreather diving operations must have knowledge of the regulatory environment, system design and safe handling procedures to execute their risk management duties.

There is ample literature on the possible adverse health effects of oxygen on divers and divers utilizing advanced diving modes receive extensive training on how to mitigate the effects. Significantly less training is received on applicable regulations, proper oxygen system design, cleaning and handling procedures. Risks associated with the use of oxygen by divers include fire and cylinder rupture. These risks are addressed by labyrinthine regulations and standards promulgated by several organizations. There is equipment marketed to divers as safe for oxygen service that is poorly designed or includes parts that are not considered oxygen compatible and there have been several diving-related oxygen fires and explosions outside of the scientific diving community. By reviewing community standards and diving-related incidents, this paper seeks to inform scientific divers of applicable regulations and best practices for oxygen system design and handling.

Regulations and Standards

Regulations promulgated by the US Department of Transportation (DOT), Occupational Safety and Health Administration (OSHA) and the US Coast Guard (USCG) have the force of law and violators may receive fines and/or imprisonment. Many standards organizations have addressed the safe handling of oxygen. The standards of primary concern to scientific divers in the US are those of ASTM International (formally the American Society for Testing and Materials), Compressed Gas Association (CGA), National Oceanic and Atmospheric Administration (NOAA), and American Academy of Underwater Sciences (AAUS). ASTM, CGA and AAUS standards are all consensus standards.

US Department of Transportation

DOT defines any compressed non-flammable gas with a pressure greater than 200 kPa (29 psig) at 20°C (68°F) as a division 2.2 hazardous material. This includes air, oxygen, helium and argon. DOT regulations apply to the transport of hazardous materials and the maintenance of hazardous material packaging for use in commerce in the US. Exemptions are provided in 49 CFR 171.1 - (d)(5&6) for "Transportation of a hazardous material in a motor vehicle, aircraft, or vessel operated by a Federal, state, or local government employees solely for noncommercial Federal, state, or local government purposes" and by an "individual for non-commercial purposes in a private motor vehicle." The DOT Pipeline and Hazardous Materials Safety Administration (PHMSA) Interpretation #11-0175 confirms these exemptions.

This is of importance to organizations using the "40%" rule for determining when to clean a cylinder for nitrox use. In 2011 DOT changed the definition of oxidizing gas from "a gas which may, generally by providing oxygen, cause or contribute to the combustion of other material more than air does" to "oxidizing gas is a pure gas or gas mixture with an oxidizing power greater than 23.5% as determined by a method specified in ISO 10156:1996 or 10156–2:2005" (49 CFR 171.8, federal register vol. 76 no. 12 pg 3319).

This is relevant because 49 CFR 173.302 requires that all aluminum cylinders authorized for oxygen use must be cleaned and inspected to comply with paragraphs 3.3.1 and 3.3.2 of Federal Specification RR-C-901D. This specifies that the fill pressure of an aluminum cylinder designated for oxygen service may not exceed 3000 psig and requires that, "After hydrostatic and any other testing, the cylinder internal surface shall be cleaned and dried to be free of moisture, oil, grease, grit, machining products, loose scale, slag, or other foreign materials." It also requires that, "Residual oil and other hydrocarbons resulting from the manufacture of the cylinder shall be removed to a level not greater than 2.5 milligrams (mg) per square foot of internal surface area, but shall not exceed 20 mg per cylinder regardless of the size of the cylinder." PHMSA Interpretation #11-0175 confirms that aluminum cylinders designated for more than 23.5% oxygen must meet these requirements. Further RR-C-901D 3.3.1 indicates that the interval of cleaning is after every visual inspection or hydrostatic test.

Occupational Safety & Health Administration

The Occupational Safety and Health (OSH) act of 1970 covers most private employers and their employees. The original act excluded coverage of federal, state, county and municipal employers. In 1980, Executive Order 12196 afforded OSH act protection to federal employees.

Section 18 of the OSH act allows states or territories to operate their own OSHA-approved safety and health programs. Territorial or state OSHA plans must cover both private and public sector employers and employees. Currently the following 22 states and territories have approved plans (Table 1).

Table 1. States with OSHA-approved safety and health programs

Alaska
Arizona
California
Hawaii
Indiana
Iowa
Kentucky
Maryland
Michigan
Minnesota
Nevada
New Mexico
North Carolina
Oregon
Puerto Rico
South Carolina
Tennessee
Utah
Vermont
Virginia
Washington
Wyoming

In addition, Connecticut, Illinois, New Jersey, New York, and the Virgin Islands have OSHA-approved state plans that cover public sector employers and employees only. Private employers in these states and territories are covered by federal OSHA (https://www.osha.gov/dcsp/osp/).

The most wide ranging provision of the OSH act is the General Duty Clause (Section 5(a)(1)(2)) which requires that:

(a) Each employer --

> (1) shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees;
>
> (2) Each employer shall comply with occupational safety and health standards promulgated under this Act and that each employee shall comply with occupational safety and health standards and all rules, regulations, and orders issued pursuant to this act which are applicable to his own actions and conduct.

OSHA standards for compressed gases include regulations for the inspection, handling, storage and utilization of compressed gas cylinders including requirements for safety release devices (29 CFR 1910.101). The regulations reference several CGA publications including: C-6-1968, C-8-1962, P-1-1965, S-1.2-1963, S-1.1-1963. These standards have been superseded by newer CGA standards. An OSHA interpretation implies that failure to comply with the most recent standards may result in citation for violating the general duty clause. If employers are in compliance with current CGA standards, violation of superseded standards should be treated as a de minimis (that is, trivial) violation and should result in no citation (OSHA interpretation #27277).

US Coast Guard

46 CFR 197 Subpart B includes regulations for commercial diving from vessels under US Coast Guard jurisdiction. Section 197.202 exempts educational institutions but Hazardous Ships' Stores as defined in 46 CFR part 147 may be of interest to organizations that are diving from inspected vessels. Section 147.60 details the storage of compressed gas and 147.85 limits the amount of oxygen that can be carried.

Risk Management

Table 2 lists the oxygen percentages at which the listed organizations require oxygen cleaning (Gabel and Janoff 1997, AAUS 2013, EIGA 2008, NOAA 2013). It is immediately apparent that several organizations use a lower threshold for determining when equipment needs to be cleaned for oxygen service.

The 40% rule has been used for years by organizations within the scientific diving community, and has proven effective in minimizing risks associated with oxygen fires. However, in light of current OSHA positions, use of the 40% rule may be problematic in the event of an incident. Therefore, as a risk management strategy, organizations utilizing advanced scientific diving modes may benefit from adopting the 23.5% oxygen threshold, thereby reducing the risk of a General Duty Clause citation.

Table 2. Oxygen percentages requiring oxygen cleaning

Organization*	Oxygen Threshold	Reference
US Navy	>25%	Mil-Std-1330D
CGA	>23.5%	CGA PS-13
NFPA	>21 or PO_2 >160 torr	NFPA Pamphlet 53M
ASTM	>25%	G126, G128, G63, G94
NASA	>21%	Report 93-27351, NASA, JSC, WSTF, 1993
OSHA	>23.5%	29CFR1910.146
OSHA	>23.5%	29CFR1910.134
OSHA	>40%	29CFR1910.430
NOAA	>40% at >200 psi (13.6 bar)	NOAA Diving Manual
AAUS	>40% at >150 psi (10.3 bar)	Standards for Scientific Diving Sec. 7.50
US Coast Guard	>40%	46 CFR 197.452 - Oxygen cleaning
EIGA	>23.5% at >30 bar (435 psi)	Safety Info 15/08/E

* AAUS - American Academy of Underwater Sciences; ASTM - American Society for Testing and Materials; CGA - Compressed Gas Association; EIGA - European Industrial Gases Association; NASA - National Aeronautical and Space Administration; NFPA - National Fire Prevention Association; NOAA - National Oceanic and Atmospheric Administration; OSHA - Occupational Safety and Health Administration

Defining an oxygen threshold above which oxygen cleaning is required without defining a pressure threshold is problematic since intermediate pressure hoses, second stages, buoyancy compensators, counterlungs and inflators may all be exposed to increased oxygen concentrations. Data for pneumatic impact testing referenced in Besson et al. (2007) indicates that the probability of ignition is extremely low in small diameter oxygen systems at pressures differentials less than 19 bar (275 psia). In 300 tests there were no ignitions of hydrocarbon contaminated foam samples.

The European Industrial Gases Association (EIGA 2008) requires oxygen cleaning at percentages greater than 23.5%, at pressures exceeding 30 bar (435 psi). AAUS uses a pressure threshold of 150 psi (10 bar) and NOAA 200 psi (14 bar). Practically, 150 psi is very close to the intermediate pressure setting of most regulators and could easily be surpassed on a malfunctioning oxygen regulator relying on an overpressure relief valve. Test data and the higher pressure threshold endorsed by EIGA and NOAA suggest that a pressure threshold higher than the AAUS standards would be acceptable from both safety and risk management perspectives.

Oxygen System Design

The successful design, maintenance and operation of oxygen systems requires knowledge of ignition sources, material properties, design practices, manufacturing techniques, cleaning procedures and the establishment of operating protocols. A basic tenant of system design is that the system should be easy to clean and easy to maintain clean. For diving systems this is best done by designing a system that can be disassembled into smaller components for easier cleaning.

Most oxygen systems used in diving have components that can act as fuel for a fire under the right conditions. With oxygen readily available, all that is needed is an ignition source for a fire to start. In addition to eliminating ignitions sources, prevention includes avoiding materials that have a low auto-ignition temperature or a high heat of combustion. Materials with a high heat of combustion can burn with enough energy to promote ignition of metals in the system. This is referred to as a kindling chain (Beeson et al. 2007).

ASTM G88-13 lists several ignition sources for high pressure oxygen systems: heat of compression, flow friction, particle impact, mechanical impact, friction, fresh metal exposure, static discharge, chemical reaction, thermal runaway, resonance, and external heat. The terms heat of compression, adiabatic compression and pneumatic impact are equivalent terms and can be used interchangeably. Heat of compression is caused by rapid compression of a gas. Figure 1 shows theoretical gas temperatures for an instantaneous pressurization from 14.7 psia to a final pressure.

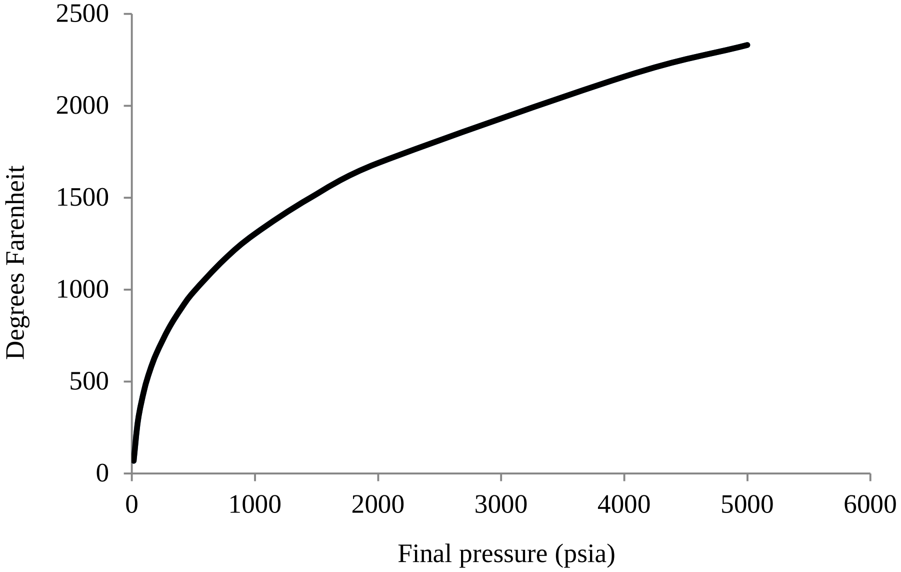


Figure 1. Theoretical maximum temperature from adiabatic compression of oxygen at an initial pressure of 14.7 psia. Data from Beeson et al. 2007.

Heat of compression is the most effective ignition source of non-metals in oxygen systems. A compression from 14.7 psia to 500 psia will theoretically result in a gas temperature of 530°C (986°F). Materials commonly considered to be oxygen compatible like PTFE (Teflon®) lined hoses and valve seats, Viton® O-rings and fluorinated lubricants are susceptible to autoignition at pressures greater than 500 psi (3.45 MPa) and temperatures greater than 500°C. Under these conditions oxygen systems do not need to be contaminated by hydrocarbons or particles to promote ignition. (Beeson et al. 2007).

To prevent heat of compression ignition, oxygen systems should avoid the use of fast opening valves like quarter turn ball or butterfly valves. Pressurization rates for small high-pressure systems should be greater than one second (ASTM G88). The risk for heat of compression ignition will be dramatically reduced if oxygen fill station designs use appropriate flow restrictors or slow opening metering valves with a maximum valve flow coefficient less than 0.05 (Doubleday and Morrison 2012). The valve flow coefficient or Cv factor is the number of gallons of water that will flow through a valve per minute with a pressure drop of 1.0 psi. This information should be available from the manufacturer.

Where possible a piece of metal tubing should be used to isolate hoses from end points that experience high heats of compression. The tubing is known as a distance volume piece and should be used immediately upstream of valves, manifolds and gauges where gas flows may terminate (ASTM G88).

Heat of compression caused rebreather fire

The most likely ignition source for the two rebreather fires reported in the pre-workshop survey is pneumatic impact in the oxygen pressure gauge hose. This hose is a particularly vulnerable part of a rebreather's oxygen system and will be covered under compatibility and cleaning.

Figure 2 shows the result of one of the reported rebreather fires. The equipment in question had been serviced 10 months previous and had approximately 80 dives since servicing. After turning on the oxygen cylinder the diver noted that the cylinder was empty. The cylinder was removed and boosted to 3000 psi (207 bar). The cylinder was reattached to the rebreather while still hot and the valve was opened in a manner normal to air cylinders. At that point a loud pop was heard followed by an eruption of flames from the regulator. After the oxygen supply had been consumed the remaining fire was extinguished with a fire extinguisher. There were no injuries.

Figure 2. Results of small, localized rebreather fire.

The pressurization rates for small diameter high pressure oxygen systems should be on the order of seconds, not tenths of seconds. The author now teaches students to angle the face of the gauge to the side but to look at the pressure gauge when opening the cylinder. As soon as the gauge needle begins to move the diver waits to finish opening the cylinder until the system has fully pressurized.

Particle impact

Particle impact in oxygen fill systems remains a concern even after oxygen cleaning. Regulators, valves, check-valves and boosters can all generate particulate contaminates during normal operations. Metals are considered more prone to particle impact then non-metals so impingement points like sharp bends and elbows should be minimized. Cooper and nickel based alloys like brass and Monel® have much higher ignition temperatures then stainless steel and can be used where particle impingement is more likely. Aluminum and carbon steel should not be used in high pressure oxygen fill systems. All piping should be de-burred before use to prevent both thin edges that are easy to ignite and burrs from breaking loose and forming particles. Tubing bend radius should be at least 1.5 times the internal diameter. Stretching and kinking bends are to be avoided (ASTM G88-13).

Oxygen flows should be limit to velocities less than 30.5 $m \cdot s^{-1}$ (100 $ft \cdot s^{-1}$) when possible and fill rates for oxygen cylinders should be kept below 60 $psi \cdot min^{-1}$ (4.1 $bar \cdot min^{-1}$) (Beeson et al. 2007; Doubleday and Morrison 2012). Oxygen systems require an inert gas blow down after assembly but before filters are installed. Filters should be placed downstream of components that are likely to generate contaminants. Filters must have regular maintenance and cleaning and should be able to withstand expected pressure differentials if clogged.

Flow friction

Flow friction ignition is poorly understood and has been difficult to study in the lab. In practice it is caused by oxygen leaking or flowing past a valve seat or O-ring seal. To prevent ignitions, perform leak checks after system assembly and as part of normal system maintenance. If leaks are found inspect sealing surfaces for chafing, abrasion, or deformity and promptly replace worn or damaged parts.

Mechanical impact

Mechanical impact is primarily a concern for non-metal seats and seals. Systems should be designed to avoid chatter or hydraulic hammering. Chatter is commonly caused by regulators, relief valves or check valves.

Of particular concern for divers using high percentages of oxygen are aluminum cylinders. There have been two cylinder fires investigated by the DOT PHMSA (WHA Report 05H010, Report No. 11287051). The Divers Alert Network has published one report (Poe 2014) and one cylinder fire was reported in the pre-workshop survey. In all four cases the fires involved 40 ft^3 cylinders designated for oxygen concentrations higher than 40%. The fires started in the cylinder neck at the base of the threads indicating that special attention to this area is warranted during cleaning and servicing. All of these fires ignited the base metal, resulting in rapidly rising pressures and explosions. Two of these fires resulted in deaths and a third in a severe maiming. Two reports cited mechanical impact of a contaminated cylinder as a possible ignition source. It has been shown that mechanical impact of contaminated aluminum can result in a promoted ignition of aluminum (Beeson et al. 2007). The cylinder described in DOT Report No. 11287051 was found to be uncontaminated and all materials were considered oxygen compatible. The ignition source was identified as mechanical impact, friction, or base metal exposure. Mechanical impact to the cylinder may have been the ignition source or friction and/or base metal exposure could have resulted from an impact to the valve. It should be stressed to divers that securing cylinders when filling and transporting is important and that failure to do so could result in explosions (Figure 3).

Figure 3. Exploded cylinder (US DOT Repot #1128705).

Harmonic resonance

Harmonic resonance ignitions are caused by reflected sound waves and are often associated with gases that reach sonic velocities and/or dead-end passages, crevices and cavities. This is generally not a concern in the simple systems used in diving. Use of proven equipment and elimination of dead-end passages will prevent harmonic resonance.

Static discharge / Electric arc / External heat

Electric arc and external heat can be the ignition source for cylinder fires and should be avoided. Static discharge is a concern for enclosed spaces with oxygen enriched atmospheres, for example, hyperbaric chambers. There is a possibility that draining oxygen cylinders in an enclosed space could raise the oxygen concentration enough to increase the risk of flash fires. Cylinders with high oxygen percentages should be drained only in a well-ventilated area.

Friction

Friction as an ignition source is primarily a concern when using boosters or oxygen compressors. Boosters and compressors may also cause heat of compression, particle impingement, and flow friction ignitions. Careful attention in their use and maintenance should be exercised. Haskel recommends separating boosters from supply and scuba cylinders by 12-15 ft (4-5 m). Fill systems should have filters upstream and downstream of boosters. Boosters should never be operated in excess of their specified cycling rate and recommended maximum compression ratios should not be exceeded.

Compatibility

When designing oxygen systems the use of metal components is recommended where possible. Where needed fluorinated plastics and elastomers are preferred over hydrocarbon based materials. Table 3 lists products generally considered oxygen compatible in well-designed systems.

Stainless Steel has been used successfully in oxygen systems but has a lower auto-ignition temperature than brass or Monel®. For components with a higher likelihood of particle impingement (e.g., valves and manifolds) brass or Monel® will reduce ignition risk.

Table 3. Oxygen compatible materials

Compatible Materials	Common Names	Common Uses
Nickel-copper alloys	Monel®	Valves, Tubing
Copper-based alloys	Brass, Bronze	Valves/Manifolds
Stainless steel (use caution)	300 series	Valves, Tubing
Fluorinated elastomers	Viton®, FKM, FPM	O-rings
PTFE,	Teflon® Dyeon™	Valves Seats, Hoses
Nylon (use caution)	Nylon	Valve Seats, hoses
CTFE, PTFE, FEP lubricants	Cristo-Lube®, Tribolube®, Krytox®	O-ring grease

EPDM, Nylon, Buna-N, and Polyurethane rubbers are the least oxygen compatible elastomers and plastics (Chou and Fiedorowicz 1997). Nylon and EPDM rubber have been used in some oxygen systems but because of their properties care should be taken to eliminate all ignition sources. Metals that are incompatible in oxygen systems include titanium and toxic metals (Beeson et al. 2007). For diving the use of aluminum should be limited to cylinders.

The ability to identify poorly-designed systems and non-compatible materials or components is important when purchasing from diving equipment suppliers. The gauge in Figure 4 was sold as part of a deluxe fitting and hose kit for use with an oxygen booster by a well-known supplier of rebreather equipment and dive gear. The gauge supplied was clearly marked "WARNING: Do not use in oxygen service". The fittings supplied used Buna-n O-rings and the hoses were nylon lined thermoplastic hoses. The valve in Figure 4 was purchased from another diving equipment supplier. The materials used were carefully specified and oxygen compatible. The valve manufacturer, however, had a different design that was specified for oxygen service and did not recommend the pictured valve. The author has also seen an oxygen booster purchased from a dive shop with a quarter turn ball valve installed on the oxygen supply line side of the booster. Good risk management practice would indicate that components should be designed for oxygen service whenever possible and that accepted design principals be followed.

Figure 4. Incompatible oxygen gauge and valve not designed for oxygen service

High pressure gauge hoses

The high pressure hoses commonly used by dive equipment manufacturers are the most problematic component in oxygen regulators from both a compatibility and cleaning standpoint. The inside of these hoses are usually lined with Nitrile (Buna-n), Neoprene or Polyurethane that have low auto-ignition temperatures and high heats of combustion.

The design also has one dead end at the gauge and a severe restriction that can result in sonic flows at the end connected to the regulator. In a hazard analysis Ryan et al. (1996) gave the high pressure hose a hazard rating of three with a likelihood of fire listed as probable. Of the three oxygen fires that were reported in the pre-workshop survey two were rebreather fires and both started in the high pressure oxygen hose. The only protection that divers have for a potential high pressure hose fire is oxygen cleaning and slow pressurization.

Fire control

Oxygen system designs should include fire control measures. A fire control plan should be included as part of a fill station operator training program and rebreather training should include fire prevention training and steps to take if a fire does occur. The first step in managing an oxygen fire in a fill system is to shut off the oxygen supply. For this reason bulk oxygen cylinders should be located away from other system components. Excess flow valves that are suitable for oxygen service can be installed to automatically shut off the downstream flow of oxygen in the advent of a line or hose rupture due to fire. If possible the system design should isolate the operator from boosters and cylinders when filling. In the field, the use of barriers or safety distance to isolate potentially hazardous equipment like boosters is recommended (ASTM G88-13).

The only way to extinguish an oxygen fire is to shut off the oxygen or lower the temperature of the ignited material below its autoignition temperature. Water is considered the best extinguishing agent. Water-based extinguishing systems should be installed were applicable, (Beeson et al. 2007; ASTM G88-13). There have been rebreather fires on boats and at least one of those spread and caused a major boat fire. If a rebreather ignites onboard, it should be immediately jettisoned overboard, if possible.

Oxygen Cleaning

When performing oxygen cleaning in the dive locker the first consideration should be the work environment. "The work area must have a cleanliness level at least equivalent to that of a clean office environment," (NSSC 2005). All work surfaces and tools should be cleaned and degreased and verified clean by bright white and black light inspection and wipe tests. Covering the cleaned work surface with a clean lint free material such as a commercially available bench liner or clean butcher paper provides a second layer of protection from contamination. Printed or paper coated with hydrocarbons are not appropriate for this use (Ryan et al. 1996). A supply of lint free gloves, micro fiber cloths and wipes should be readily available.

Available cleaning methods include mechanical and chemical. Mechanical methods commonly used in the dive locker include ultrasonic cleaning, brushing, spraying and swabbing. Chemical cleaning can involve aqueous, solvent and chemical-based cleaning agents. Chemical cleaning can be accomplished by immersion or dip cleaning but it is usually more effective when combined with a mechanical method. Because several aqueous cleaners are non-corrosive, non-toxicity and easily disposed of, they are usually preferred for use in the dive locker. The cleaning process takes place in three stages followed by an inspection. Once each stage of the cleaning process has started it should be not be interrupted until completed.

The first stage is an initial item inspection and pre-clean. Tanks, regulators and fill station components should be disassembled and inspected. Inspected items which are visibly clean may eliminate the pre-cleaning step and proceed directly to the oxygen cleaning and final inspection steps (DOD, MIL-STD-1330D). The goal of pre-cleaning cleaning is to remove salt, corrosion and dirt deposits. Regulator parts should be cleaned according to the manufacturer's servicing recommendations and should only be done by staff with training to service the regulator. The pre-clean often involves a hypersonic cleaning or soaking of chromed metal parts in a specified cleaner or in a mild acidic solution. Some manufacturers recommend that the regulator should be neutralized in a baking soda water bath before rinsing. Strong acids like muriatic should not be used and care must be exercised as prolonged exposure to the bath can remove chrome. Five minutes of immersion should be a sufficient for most parts. Use a liquid dishwashing detergent and water for pre-cleaning plastic, rubber, silicone or anodized aluminum parts. Using an acidic bath on these parts may damage or degraded them. Silicone and fluorinated greases common to diving can be difficult to remove particularly in threaded areas. Most pre-cleaners will have limited effectiveness without agitation and hand scrubbing is usually often the best alterative (MIL-STD-1330D).

When pre-cleaning cylinders, the exterior should be cleaned with detergent and water and loose paint should be removed using household non-abrasive cleaning or scrapers. Tank threads should be cleaned using a nylon bristle brush and either Isopropyl Alcohol, a non-toxic household cleaner or a product like Christo-Kleen® if fluorinated lubricants are a problem.

For cylinders, the pre-clean includes inspection to determine if an abrasive tumbling is needed. If cylinders contain obvious contaminates (i.e., rust, aluminum oxide powder, oil or grease residue) or have been used for air service, pre-cleaning should include tumbling using a slurry of ceramic or aluminum oxide chips, water and a liquid dishwashing detergent. Luxfer recommends four to six cups of tumbling medium per gallon of water plus two teaspoons of liquid dish washing detergent. Catalina recommends 17 cups of tumbling media to 12 cups water with the addition of a small amount of dishwashing detergent for a standard 80 ft^3 cylinder. Cylinders should be tumbled for 15-30 min depending on the level of contamination. If cylinders are new or previously cleaned for oxygen service and there are no visible contaminates the abrasive pre-cleaning tumble is not required. Tumbling media that are used for pre-cleaning should not be used for the oxygen cleaning step.

If pre-cleaned items are not to proceed immediately to the oxygen cleaning step they should be rinsed. Potable tap water is adequate for rinsing in many parts of the world. Hard rinse water should be avoided as it is less effective at rinsing and may leave a residue. If the available water is not adequate then deionized, filtered or distilled water should be used. A good test is to evaporate a sample of rinse water in a clean white container and to inspect for hard water residue or particulates. Humans with vision corrected to 20/20 can detect particles down to 50 µm (Beeson et al. 2007). In practice, an evaporated sample of water intended for rinsing should contain no particles or residue. Warm water is a more effective rinsing agent and rinse water should be maintained at 120-140°F (50-60°C) (MIL-STD-1330D). Rinsing can be done in the ultrasonic bath, by immersion in water with agitation, in flowing water or by spraying. After rinsing, components should be dried using a heat gun, oil free air or nitrogen. If air drying, parts should be protected from aerial contaminates that may accumulate because of the longer drying time. Dried cylinders should be caped and parts should be stored in clean reclosable polyethylene bags (Ziploc®) (ASTM G93).

The next stage in oxygen cleaning is a degreasing wash using an appropriate cleaner. Detergent cleaning agents generally work best at a temperature range of 140-170°F (60-77°C). The manufacturer's temperature recommendation should be followed as closely as possible. Table 4 lists several acceptable cleaners by reference and dilution. Other cleaners are available for use. Important selection criteria for cleaners include: water soluble, non-toxic, low foaming and free rinsing (Doubleday and Morrison 2012) and in all cases the manufacturer's recommendations should be followed.

Cylinders that have received an abrasive pre-cleaning tumble can be tumbled using the cleaning solution diluted to the appropriate strength. For new or previously oxygen cleaned cylinders that did not receive an abrasive tumble, a tumbling wash using non-abrasive glass bead media with the cleaning solution will augment cleaning (Boyd and Kent 2002). The degreasing tumble should last 10-15 min.

Table 4. Common cleaning agents and recommended dilutions

Cleaner	Source	Dilution in water
Navy Oxygen Cleaner (NOC)	US Navy MIL-DTL-24800	100% and 50%
Blue Gold Industrial Cleaner®	CGA[1]	5%
Brulin Formula 815 GD ™	CGA[1]	5-20 %
Beyond 2001®	CGA[1]	5%
Chemclean 2011	CGA[1]	1-6 oz/gallon
Crystal Simple Green	NOAA[2]	10%
Alconox	NOAA[2]	1%
Special Cleaner	GSMoT[3]	1%

[1] Compressed Gas Association 2000 Directory of Cleaning Agents for Oxygen Service
[2] NOAA Diving Manual 5th Edition
[3] Global Scuba Manufacturing of Texas LLC

As in the pre-cleaning step, cylinder and valve threads should be given special attention as this is an area where particles are generated or collect that can create a kindling chain. A thorough cleaning with an oxygen clean nylon bristle brush and the diluted cleaning solution is required. Immersing the threads for 10 min in cleaning solution before brushing will help to loosen and suspend contaminants.

Regulator parts and tank valves can be cleaned by immersion alone but immersion in a heated ultrasonic bath will provide more consistent result and should be used whenever possible. Most supply line components (e.g., valves, check valves, and filter bodies) can be cleaned this way also. The recommended cleaning time is 10-15 min depending on contamination.

One breathing gas system component that is particularly difficult to clean is the sintered filter. Due to the design these filters have a high number of entrapment areas. This raises the concern for entrapment of contaminants, cleaning solutions, and rinse water. If oxygen clean replacements filters are available from the manufacturer it is recommended that these filters be replace at the time of servicing. If not, then ultrasonic cleaning times should be extended to 30-60 min and filters should be dried in a 300-400°F (150-200°C) oven (Norman Filter Company).

Components that cannot be cleaned in an ultrasonic bath such as tubing and long hoses are best cleaned using a circulating pump to move the cleaning solution through the tubing or hose. Seal-less, centrifugal magnetic drive pumps with polypropylene or Delrin® housings and impellers will work and the inlet and outlet can be plumbed in to a heated bath. To ensure that entrapment areas and fittings are contamination free the solution should be circulated through the hose or tubing in both directions. All pre-cleaning steps should be carried out before oxygen cleaning hoses and tubing.

High pressure regulator hoses

It may be more efficient to simply replace hoses then to try and clean them. If hoses are to be cleaned then an ultrasonic bath should be used if the hose is small enough to fit. If not, then the hose can be immersed in the cleaning solution. In either case the hose must be filled from the female end with cleaning solution before immersion and cleaning times should be increased. The Scuba Industries Trade Association (SITA), a United Kingdom trade association, recommends 15 min for ultrasonic cleaning and several hours for immersion cleaning, followed by three to five rinse cycles. A syringe can be used to introduce fresh cleaning solution at intervals when immersion cleaning, (SITA 2007).

Final rinse

No degreasing detergent is oxygen compatible and a through final rinse is required. Final rinsing of oxygen system components should be completed immediately following oxygen cleaning. If delayed, detergent residue and the suspended contaminates will dry on the components and the degreasing step will need to be repeated (ASTM G93 2011). Rinse as described in the pre-cleaning step and proceed immediately to drying. A sample of both the degreasing solution and the rinse water should be saved for inspection. Once final drying has been completed cylinders and components should be immediately inspected and reassembled or stored as described in the pre-cleaning step. After the finale rinse and dry it is best to double bag the part and include a label between the bags with a copy of the inspection documentation.

Inspection

Inspection is an important component of oxygen cleaning. Not all surfaces can be inspected, however, careful inspections of surfaces that can be are useful in validating the cleaning procedure used. Most dive lockers are not equipped to do a quantitate analysis of parts however there are qualitative test that can be used to verify cleanliness.

Inspection of oxygen cleaning solution

A sample of the cleaning solution in a clear vial should be inspected using a bright white light after cleaning. The appearance of an oil sheen or particulates is justification for replacing the cleaning solution and re-cleaning. Cleaning solution that passes inspection can be re-used but should be replaced at regular intervals. The Navy recommends changing the cleaning solution after five cleaning cycles (NSSC 2005).

Rinse water shake test

The rinse water shake test relies on the assumption that the oxygen cleaning process chosen is effective and that any hydrocarbons have been dissolved or suspended in the cleaning solution. If this is the case and all of the cleaning solution has been removed, so have any hydrocarbons. Depending on the cleaning solution used there are two ways to check the effectiveness of the final rinse. Many of the cleaning solutions used are alkyne and the technician can compare the pH of the rinse water sample to the pH of the water supply. The pH of the final rinse water should be the same as that of the water used to rinse. The second test involves placing a sample of the final rinse water in a clear vial and unused rinse water in a second clear vial. Both vials are shaken and compared over a period of time. Because the cleaning solution foams if any residue is left in the final rinse water, bubbles or foam will persist much longer in the final rinse water sample then in the water sample. If it is determined that the rinse water sample contains cleaning solution then rinsing should continue. If the cylinder or part was dried before the test was conducted it should be re-cleaned and rinsed again (NSSC 2005; Boyd and Kent 2002).

Direct visual inspection – white light

White light inspection is a common test used to detect the presence of particles larger than 50 µm, oil films or grease. For parts inspection, a bright flashlight with a xenon or LED bulb held at no more than 18 in (46 cm) is adequate. For tanks, a high quality tank inspection light can be used. The thread and neck area should be carefully inspected with a flashlight and magnifying mirror. If contaminants are detected the item should be re-cleaned (ASTM G93, NSSC 2005, Doubleday and Morrison 2012).

Direct visual inspection – black light

Black lights that radiate in the 250-370 nm range will cause many oils and greases to fluoresce. Unfortunately, fluorocarbon greases and oils that are commonly used in compressors and to lubricate O-rings in oxygen systems do not fluoresce so black light inspection by itself is not indicative of a contaminant-free cylinder or part. On parts, lint or dust that fluoresces during inspection maybe removed by blowing with oxygen compatible air, wiping or suctioning. If blotches or smears appear, the cylinder or part should be re-cleaned. Black light inspection can also give false positives with some non-metallic materials. If after re-cleaning the same area fluoresces and other tests are negative a false positive can be assumed (ASTM 93).

Wipe test

Areas that are difficult to visually inspect can be assessed by wiping with a clean white lint free cloth or wipe. The wipe should be inspected with both bright white light and black light. If the wipe is discolored, the cylinder or part should be cleaned again. One caveat is that the inspector should not apply enough pressure when wiping to remove surface oxides (ASTM 93).

Water break test

This test can be performed by using a spray bottle of clean water to spray the part in question. This test is best when performed on horizontal surfaces. The water should form a thin unbroken film. Water beading would be an indication of oil or grease contamination. On rounded or vertical surfaces look for uniform water sheeting with no beading. Water beading indicates the need for re-cleaning. Water collecting at the bottom of convex surfaces should not be confused with beading.

Validation

Validation of a cleaning procedure can be done by most organizations using the method outlined in MIL-STD-1330D. One by four inch by 1/16 or 1/8 inch 316 stainless steel coupons are first oxygen cleaned and weighted. Each coupon is then contaminated with 75-100 mg each, of hydrocarbon grease, silicon grease and fluorinated grease. After oxygen cleaning a second time the coupons are re-weighted and the procedure is considered effective if 99.9% of contaminates by weight have been removed.

Documentation

Oxygen cleaning documentation should be an important part of the risk management procedures for any organization. Both documentation of the procedure used and individual records of the items cleaned should be maintained. The oxygen cleaning procedure defines approved cleaners, required cleaning steps, technician training requirements and method validation.

Individual component cleaning records should include:

- Cleaning procedure
- Item(s) cleaned
- Date item(s) cleaned
- Pre-cleaning and cleaning agents used and dilutions
- Temperature of cleaning agents and rinse water
- Cleaning and rinse times
- Verification of cleaning agent removal (shake test)
- Hydrocarbon analysis – (visual white and black light)
- Particulate analysis – (rinse water and part inspection)

- Soft goods replacement and cleaning (i.e., O-rings, seals, etc.)
- Name of person(s) performing above operations

Reassembly

When reassembling it is important that only oxygen compatible soft goods that have been oxygen cleaned be used. Just as in the cleaning steps tools and surfaces must be O_2 clean and technicians must wear gloves. O-rings and tank valve threads should be lubricated very lightly. As previously stated, under conditions such as impact and heat of compression, fluorinated greases can autoignite. Therefore, the minimum amount should be used. Follow the manufacturer's directions but in general static O-rings do not need lubrication to function properly.

Oxygen Systems Maintenance

Appropriate service intervals for regulators are well defined by the manufacturer. The situation with cylinders and fill stations is less clear. Federal Specification RR-C-901D states that after any hydrostatic or other testing the cylinder's internal surface shall be cleaned of any oils and grease. If the annual cylinder inspection is included in the definition of testing then it is clear that cylinders should be cleaned at the time of inspection. Gas blenders should always inspect the cylinder valves for silicon grease or other contaminates before attaching fill whips. If needed a wipe test can be performed and the wipe inspected under bright white and black lights. Anytime it is suspected that a cylinder has been filled from a contaminated source it should be re-cleaned and inspected. A good practice to prevent contamination is to use only oxygen compatible lubricants when servicing all diving and fill station equipment regardless of whether it is intended for use with high concentrations of oxygen or air. A separate work area can also be established for servicing equipment like cameras that use silicone grease.

Operationally generated contaminates can be produced by: compressors, boosters, valves, check-valves, and quick-disconnect fittings. Other than medical oxygen kits, which see little use and are generally stored in sealed cases, oxygen and nitrox equipment used in the scientific diving community is subject to regular use in harsh environments. The Scuba Industries Trade Association (SITA 2007) recommends the following cleaning intervals:

Cylinders	15 Months
Scuba Regulators	Manufacturer's recommended service interval
Oxygen Storage and Delivery Systems	Not to exceed 12 Months

As a best practice in the US scientific diving community a 12-month service interval for all oxygen and nitrox systems seems reasonable unless a documented inspection program indicates that the interval can be increased.

Conclusions

AAUS and other organizations conducting scientific diving should review their current oxygen cleaning and pressure threshold limits. Despite the safety record of the 40% rule in scientific diving adopting a lower percentage threshold and higher pressure threshold for oxygen cleaning standards maybe a better risk management strategy.

Best practices for oxygen handling in scientific diving programs should include the following recommendations:

- It is recommended that the oxygen cleaning standard be validated. The standard should be approved by the Diving Control Board. The standard should define:
    - Required technician training qualifications
    - Approved pre-cleaning and cleaning methods
    - Cleaning solutions and temperature ranges,
    - Approved rinse methods and temperature ranges
    - Approved drying methods Storage requirements
    - Required documentation
    - Service intervals for oxygen equipment

- Oxygen fill station and gas blending operational standards should include:
    - Required technician training qualifications
    - Fire control plan
    - Maintenance schedule

References

American Academy of Underwater Sciences [AAUS] Standards for Scientific Diving Manual, Section 12: Rebreather Standards; 2013.

ASTM International

G88-13, Standard Guide for Designing Systems for Oxygen Service

G93-03 (Reapproved 2011), Standard Practice for Cleaning Methods and Cleanliness Levels for Material and Equipment Used in Oxygen-Enriched Environments

G127-95 (Reapproved 2008), Standard Guide for the Selection of Cleaning Agents for Oxygen Systems.

Beeson HD, Smith SR, Stewart FW. Safe Use of Oxygen and Oxygen Systems - Handbook for Design, Operation, and Maintenance, 2nd Ed. ASTM International 2007; MNL 36-2nd. Online version available at: http://app.knovel.com/hotlink/toc/id:kpSUOOSHD9/safe-use-oxygen-oxygen/safe-use-oxygen-oxygen

Boyd D, Kent G. Converting Dive Tanks for Oxygen Service with GMC Oxy-Safe Products, 2nd Ed. Global Scuba Manufacturing of Texas LLC, 4674 Priem Lane, #402 Pflugerville, TX 78660. www.linkedin.com/company/global-scuba-manufacturing-of-texas-llc

Chou TC, Fiedorowicz A. Oxygen compatibility of polymers including TFE-Teflon®, Kel-F® 81, Vespel® sp-21, Viton® A, Viton® A-500, Flourel®, Neoprene®, EPDM, Buna- N and Nylon 6,6. In: Royals WT, Chou TC, Steinberg TA, eds. Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Eighth Volume, ASTM STP 1319. American Society for Testing and Materials, 1997: 319-49.

Compressed Gas Association

CGA PS-13-2007 Definition of a Threshold Oxygen- Mixture Concentration Requiring Special Cleaning of Equipment. 1725 Jefferson Davis Highway, Suite 1004, Arlington, VA 22202.

2000 Directory of Cleaning Agents for Oxygen Service. Compressed Gas Association, Inc., 2000. 1725 Jefferson Davis Highway, Suite 1004, Arlington, VA 22202. infohouse.p2ric.org/ref/31/30468.pdf

Department of Defense, MIL-STD-1330D. Standard Practice for Precision Cleaning and Testing of Shipboard Oxygen, Helium, Helium-Oxygen, Nitrogen, and Hydrogen Systems, 1996. www.everyspec.com

Department of Transportation, Pipeline and Hazardous Materials Safety Administration http://www.phmsa.dot.gov/

DOT PHMSA, Inspection / Investigation Report No. 11287051. http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Files/Press%20Release%20Files/11287051_Scuba_Cylinder_Final_Report.pdf

DOT PHMSA, WHA Report 05H010. Fire Origin Investigation Involving a DOT 3AL Cylinder Failure in Luraville, FL. http://www.phmsa.dot.gov/pv_obj_cache/pv_obj_id_24DC2E7C278489CA87013EEC9115AA028F7A2301/filename/05H010_Final_Report_12_17_06.pdf

DOT PHMSA Interpretation #11-0175 http://www.phmsa.dot.gov/portal/site/PHMSA/menuitem.6f23687cf7b00b0f22e4c6962d9c8789/?vgnextoid=05c8a530e8983310VgnVCM1000001ecb7898RCRD&vgnextchannel=aa8cd3c1af814110VgnVCM1000009ed07898RCRD&vgnextfmt=print

49 CFR 171.8, federal register vol. 76 no. 12 pg 3319, http://www.gpo.gov/fdsys/pkg/FR-2011-01-19/html/2010-33324.htm

Doubleday A, Morrison C. Oxygen Equipment Service Technician Student Manual. Technical Diving International, 2012.

EIGA. Safety Principles of High Pressure Oxygen Systems. European Industrial Gases Association 2008. http://eiga.web1.apollo-com.be/fileadmin/docs_pubs/Info_15_08.pdf

Federal Specification RR-C-901E,. Cylinders, Compressed Gas: Seamless Shatterproof, High Pressure Dot 3aa Steel, and 3al Aluminum, 2003. http://everyspec.com/

Gabel H, Janoff D. Use of oxygen-enriched mixtures in recreational scuba diving – is the public being informed of the risks? In: Royals WT, Chou TC, Steinberg TA, eds. Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Eighth Volume, ASTM STP 1319, American Society for Testing and Materials, 1997: 34-41.

Poe J. Trust but verify. Alert Diver, 2014; 30(3):61-3. https://www.diversalertnetwork.org/diving-incidents/trust-but-verify#.VUfJG7dFDcs

NOAA Diving Manual, 5th edition. Dinsmore D, Bozanic J, eds. Best Publishing Co., 2013: pg 7-1 to7-35.

Norman Filter Company https://www.normanfilters.com/manuals/SS%20Element%20Cleaning%20Instructions%20PSM04-19.pdf

Occupational Safety & Health Administration (OSHA)

Occupational Safety and Health Act of 1970, General Duty Clause, Section 5(a)(1)(2)

29 CFR 1910.101 https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9747

OSHA interpretation #27277
https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=27277

https://www.osha.gov/dcsp/osp/

Ryan R, Walsh M, Pomerantz M. Regulator materials compatibility, cleaning and lubrication considerations for enriched air diving. American Academy of Underwater Sciences Workshop, 1996; 8pp.

SITA. Diving Equipment in Oxygen Service. Scuba Industries Trade Association. 2007.
http://www.sita.org.uk/pdf/sita-02-clean-2012-1.doc

NSSC. Topside Tech Notes, Naval Sea Systems Command, vol. VI Issue 2, 2005, pg 1-6.
https://aquatec.files.wordpress.com/2011/03/diver-life-support-system-cleaning.pdf

QUESTIONS AND DISCUSSION

JIM HAYWARD: Are you implying that in transport there was a ding to the valve that caused enough separation for gas to leak gas?

JEFF GODFREY: The speculation on this one is, and, again, this is speculation, this killed the guy, and it pretty much took out the side of his house. So through the forensic -- I will have that report available. You will be able to look this up, read the whole thing, all the gory details. Some of the reading is not very nice on it. It basically took out the side of the house and he died as a result of this. The suspicion was he said, I have got to go back in and get some cylinders. He had a bunch of cylinders stored loose in a closet. While he was moving cylinders, this cylinder fell down and hit another cylinder. It was the actual mechanical impact. Whether it was because a valve hit and turned and it was a friction impact or whether it was the mechanical impact of the valve against the threads that ignited the fire.

SIMON TALBOT: Do they have any idea how recent the service was, the last service?

JEFF GODFREY: It was within a year.

RICHARD PYLE: I would love to see our community to come up with a set of standards for cleaning. I would love a guidance to follow because I make it up as I go along. And the question I have concerns taking the valves off the cylinders to get in the airplanes. Do we do a full O2 service when we arrive at the destination or just make sure the threads are clean?

JEFF GODFREY: I use the little PVC caps to go on the top of the cylinders. And then I assume that because I capped it there are no contaminants. Our first run we went to Australia. And we were out rolling cylinders up and down the pier there full of dish detergent. They had no clue what we were trying to do.

JEFF BOZANIC: You cannot actually have the caps in the cylinder, however, when they go through TSA.

JEFF GODFREY: Yes, as long as they can unscrew them.

JEFF BOZANIC: No, not any longer. I have had six cylinders confiscated because I had caps in them. I now keep them on me. I transport them in my carryon. I take any caps out before I go through TSA. And then after TSA, I can put caps back in. The TSA regulations say they must be open for inspection.

DOUG KESLING: My suggestion would then be to seal those in a Ziploc bag that is open but clear.

JEFF BOZANIC: I have been told I cannot have them in anything nor can I have anything blocking the neck openings whatsoever.

DOUG KESLING: But they can open the plastic and inspect them.

JEFF BOZANIC: Their argument is if you had any means of sealing a toxic gas in the system, then for their perspective it is considered hazardous.

DAN MONSON: I just would like to say I did go through a process, basically a trip from hell, to go to Russia one time because my cylinder had the top just barely on. I asked the check-in people, is this okay? They said, yes so I checked the bag. Got to my designation, and the rebreather was gone. Someone had pulled it without telling me. Just left me the little note saying it had been checked by TSA. It took me a lot of time to figure out where it was.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

Defensive Dive Profile Planning

Neal W. Pollock

Divers Alert Network and Center for Hyperbaric Medicine and Physiology,
Duke University Medical Center, Durham, NC
npollock@dan.org

Abstract

Defensive dive planning requires a good understanding of factors that can affect decompression stress, and a knowledge of practical strategies to control risk. Our increasing reliance on dive computer technology demands an understanding of the limits of decompression algorithms and decisions that can influence outcomes.

Keywords: algorithm, decompression, safety

Introduction

Limited gas supply and inefficient thermal protection once worked to cap exposures, and subsequently the decompression stress experienced by the typical diver. Increased choices for gas supply and improved thermal protection enabled divers to markedly extend their range. Dive computers have further increased flexibility. The square profiles of the past are largely replaced by complex dive profiles that are no longer tracked by divers, but by diver-worn computers.

Decompression safety may be achieved by staying within dive computer or dive table limits, but it is also possible for decompression sickness (DCS) to develop after dives that remain within prescribed limits. Dive computers generally work as designed, but the mathematical algorithms do not evaluate many of the factors that can alter the decompression risk of a given exposure. Building in modest buffers in every step of the diving process can help to ensure good outcomes. We will consider concepts important for conservatism, some of the pitfalls that must be overcome, and practical strategies for defensive dive profile planning and implementation.

Conceptual Control

Know the risks

Diving is used for both work and pleasure and in the vast majority of cases is concluded with no problems. The risks, though, should not be ignored. Understanding them is a critical step in preparedness. Early recognition of issues can allow most to be resolved before they become troublesome.

Take responsibility for safety

No other person or any device should have complete authority over individual activity. Some divers will follow a computer without thinking about what it does not know, or expect it to get them out of trouble they create, but any person or device can make mistakes. Divers must be actively and intentionally involved in every step of every dive, and able to lead when necessary.

Divers must understand the available tools. Recognizing that reliance on dive computers is now the norm, it is important for divers to have a clear conceptual understanding of how the decompression algorithms they rely upon actually work. It is equally important to know what they do not consider, and that computational models can be wrong. Both understanding and backups are essential.

Evaluate information critically

It is a human quirk to hold what can sometimes be undue faith in what appears on a screen or gauge, whether it is a gas gauge or a dive computer screen. Divers must maintain open, critical minds to fully assess information and use it appropriately.

Know risk tolerance

Risk tolerance varies between individuals, institutions, and situations. It generally increases proportionally with the perceived benefits and decreases inversely with the severity of the potential injury. Establishing both institutional and individual comfort zones will help coordinate practice.

Maintain a safety-oriented mindset

When rules are broken or limits are violated with no obvious repercussions, there can be a gradual shift away from thinking of them as important. This can lead to 'normalization of deviance,' when something once thought of as unacceptable becomes acceptable. The problem is that decompression stress is an invisible hazard. We do not change color as we fill with inert gas and decompression stress may not be perceived until a critical stage is reached. We can feel good right up to the point that we feel very bad. Vigilance is required to maintain good practice.

Reinforce safety messaging

Thinking or teaching "do this or get hurt" can be counterproductive to safety-oriented practice. As discussed above, the first time the line is crossed without injury the rule will become less important. After it has been crossed a few times the rule may seem irrelevant or the individual may perceive himself or herself as being endowed with special protection. Both of these beliefs can lead to poor choices. Flipping the focus to "do this and be safer" can provide much healthier reinforcement. When nothing bad happens the positive benefits of the practice are reinforced. Both peace of mind and good practice are promoted.

Avoid mission creep

Even the best intentions can be overcome by trouble-free diving and complacency. This can be seen on multi-day dive trips. The intensity of diving frequently increases as the trip continues. It is not uncommon for a person developing DCS during a trip to describe their most conservative practice as their norm. Electronic dive logs, however, frequently show an erosion of safety buffers over successive days.

Figure 1 depicts three dives in a series ultimately ending with mild symptoms of decompression sickness (DCS). In the first the diver maintained a vertical cushion between his decompression ceiling (shown as the red block, produced with a gradient factor setting of 30/70 and a Buhlmann model) and a post-decompression cushion (shown from the end of the red block). The diver cleared his decompression before reaching the prescribed stop depth and then added more stop time before surfacing. He also maintained a high PO_2 through most of the decompression, facilitating inert gas elimination. In the second dive it can be seen that both ceiling and post-decompression cushions were eliminated, with the diver surfacing almost immediately after the decompression obligation was cleared. A high PO_2 was maintained throughout the decompression. In the third dive, the diver remained right at the decompression ceiling for a prolonged period, then directly ascended as soon as the prescribed decompression period ended. In addition, the PO_2 setpoint was reduced during the final phase of the decompression. While this would save oxygen and make buoyancy control easier, the gradient promoting inert gas elimination was compromised. The diver developed symptoms after the third dive, expressing the belief that he always dived extremely conservatively. The incremental change in the profiles did not support this view.

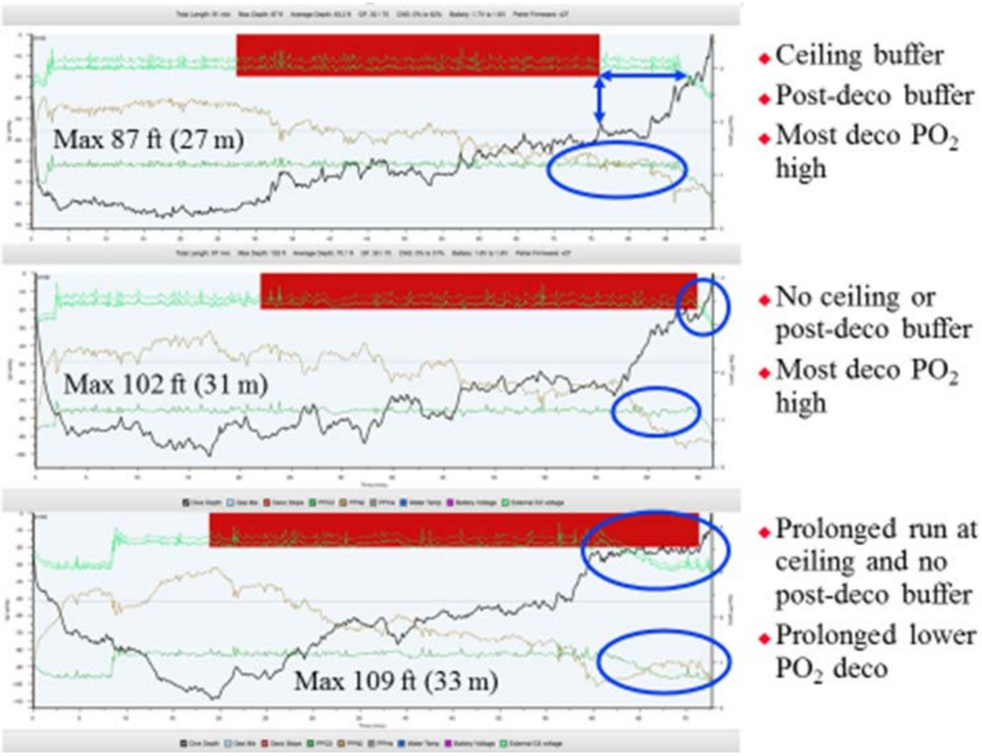


Figure 1. The three dive profiles depict a pattern shifting from one with substantially buffering from the decompression ceiling and after decompression clears to one clearly riding the limits.

Pick teams well

The mindset and practice of others in a group can radically affect individual risk. Selecting those with appropriate and complementary goals, objectives, and attitudes can help to ensure safe activity. If anyone is pushed beyond his or her comfort zone, the default of personal responsibility is a critical protection.

Use tools to defend practice

Selecting appropriate conservatism settings on dive computers can reduce the need to argue over no-decompression limits or decompression profiles. Differences in the selected settings may prompt discussions that help everyone gain insight. The critical mind is essential, weighing the merits of arguments. Further discussion is found in an accompanying paper from this meeting (Pollock 2016).

Practical Strategies

Solid knowledge, awareness, critical thinking, and partner selection provide the foundation to promote good diving practice. Implementation requires some additional consideration. Employing a number of small buffers can produce a web of protections that has minimal impact on the limits while maintaining a high degree of conservatism.

Dive profiles

The dive profile is the single most important determinant of the ultimate decompression risk of a dive. The shift from square profiles to multi-level profiles can be used to lessen decompression stress. The optimal ascent profile will employ increasing periods of time at each progressively shallower step. Ascent rate should follow a similar curvilinear pattern, slowing progressively through the ascent.

Figure 2 depicts a dive to 164 fsw (50 msw) that resulted in serious DCS symptoms. The decompression dive was carried out with an ascent profile closely following the prescribed limits (Buhlmann algorithm with a gradient factor (GF) setting of 15/85). GF_{low} (15% of the M-value) favored a deep(ish) stop that cleared quickly during ascent. GF_{high} (85% of the M-value) provided little buffer from the M-value limit (100%) that is known to produce bubble and even DCS with some exposures. The diver went directly to the decompression ceiling and added no post-decompression buffer before surfacing. The profile suggests that the diver trusted that the guidance provided by the algorithm was sufficient. For this individual on this dive, adequate conservatism was not maintained.

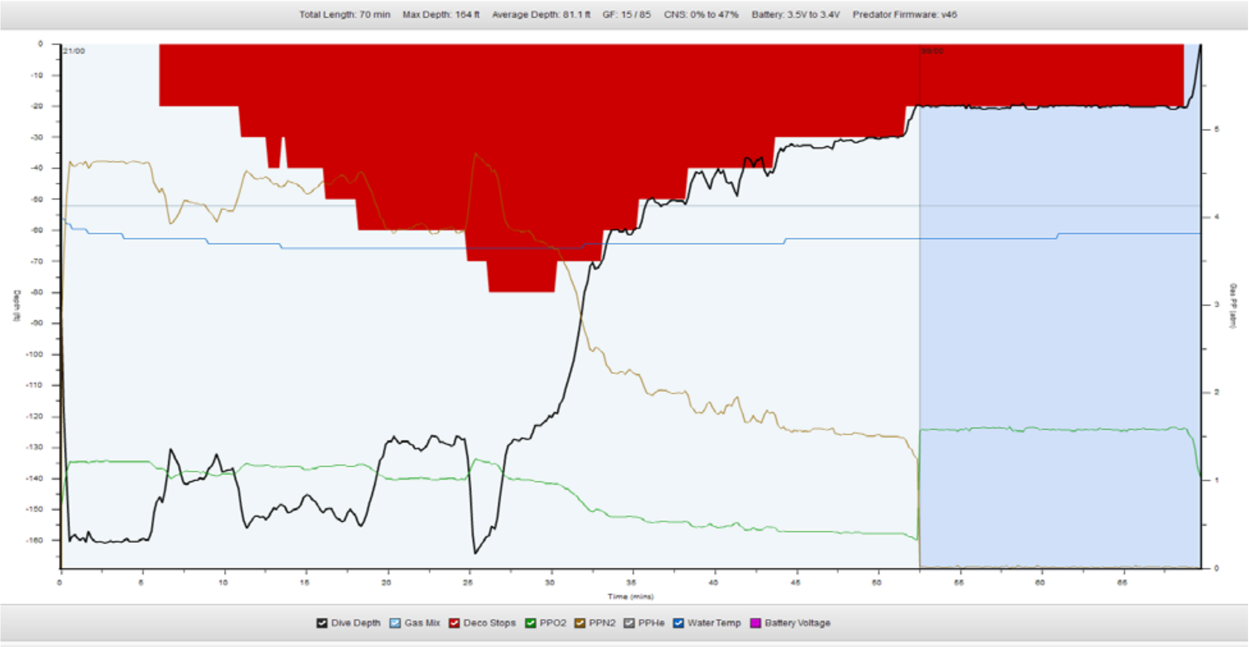
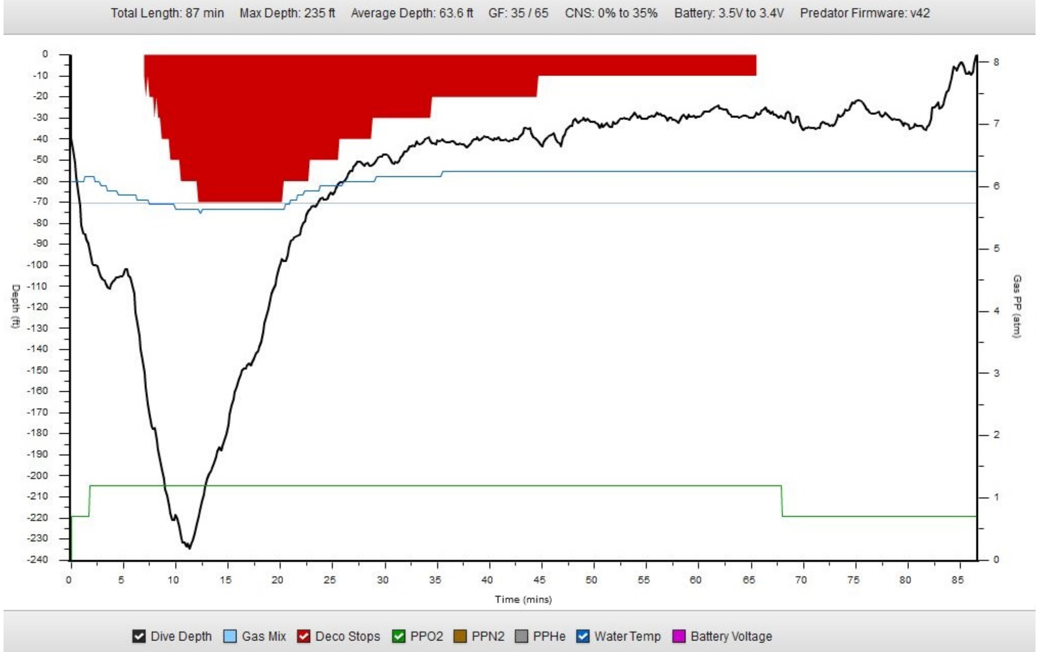


Figure 2. A 164 fsw (50 msw) decompression dive resulting in DCS (GF 15/85).

Figure 3 depicts a 235 fsw (72 msw) decompression dive that could be described as exceptionally conservative in terms of the decompression profile. The GF setting was 30/65. A GF_{low} of 30 gets the diver much further off the bottom than a GF_{low} of 15, creating some increase in the supersaturation of fast tissues, but reducing the sustained uptake of inert gas by slow and intermediate tissues. A GF_{high} of 65 provides a much greater buffer from the M-value limit than a GF_{high} of 85, reducing the peak supersaturation of this exposure. In addition to establishing conservative settings, the diver did not approach these limits, instead incorporating additional substantial ceiling and post-decompression buffers. Essentially, the diver cleared decompression 10-20 ft (3-6 m) deeper than was required by the dive computer algorithm, and then extended the time spent in the relatively shallow zone after the obligatory stop period was concluded before surfacing. This may be a more conservative ascent profile than required, but it certainly provided a worry-free endpoint based on the absence of bubbles seen in the heart during post-dive monitoring (Figure 4).



Total Length: 87 min Max Depth: 235 ft Average Depth: 63.6 ft GF: 35 / 65 CNS: 0% to 35% Battery: 3.5V to 3.4V Predator Firmware: v42

☑ Dive Depth ☐ Gas Mix ☑ Deco Stops ☑ PPO2 ☐ PPN2 ☐ PPHe ☑ Water Temp ☐ Battery Voltage

Figure 3. A 235 fsw (72 msw) decompression dive profile with substantial ceiling and post-decompression buffers (GF 35/65).

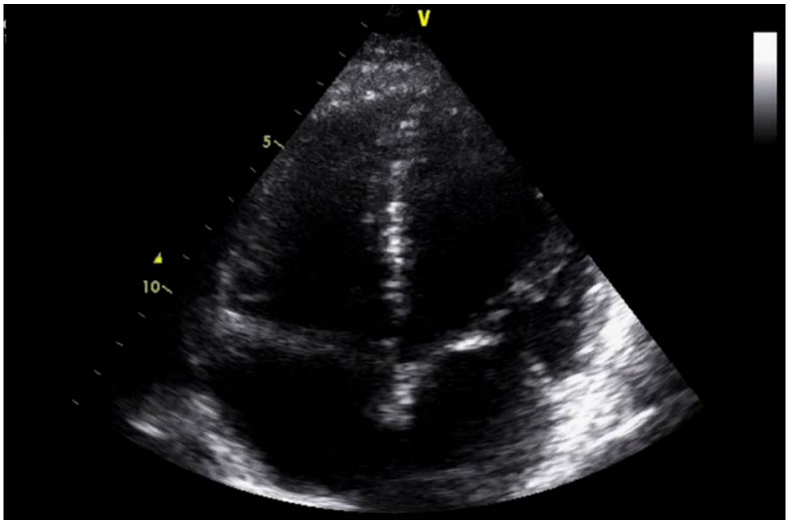


Figure 4. Still image of a bubble-free heart visible during two-dimensional ultrasonic monitoring following a conservative dive profile (see Figure 3).

Figure 5 depicts a dive to 330 fsw (101 msw) with an ascent profile that modestly adheres to the algorithm-defined gradient factors profile. There is a modest, intermittent ceiling buffer and modest post-decompression buffer. The GF setting was 60/85. The GF_{low} of 60 allows a fairly extreme direct ascent off the bottom, likely creating marked supersaturation of fast and even fast-intermediate tissues. The GF_{high} of 85 provides a modest buffer from the M-value limit. The dive did not produce symptoms, but did generate an unwelcome high post-dive bubble load (Figure 6). The peak grade of venous gas emboli (VGE) in the right heart was IVc, the second highest score on our current nine-point ordinal scale.

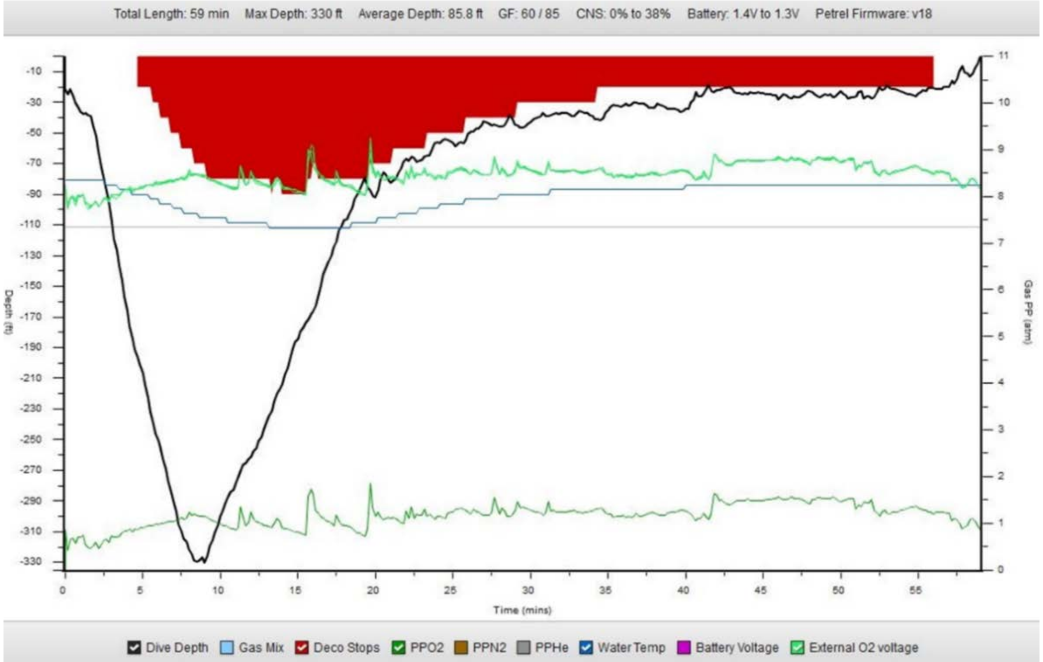


Figure 5. A 330 fsw (101 msw) decompression dive modestly adherent to the prescribed ascent profile with modest transient ceiling and post-decompression buffers (GF 60/85).

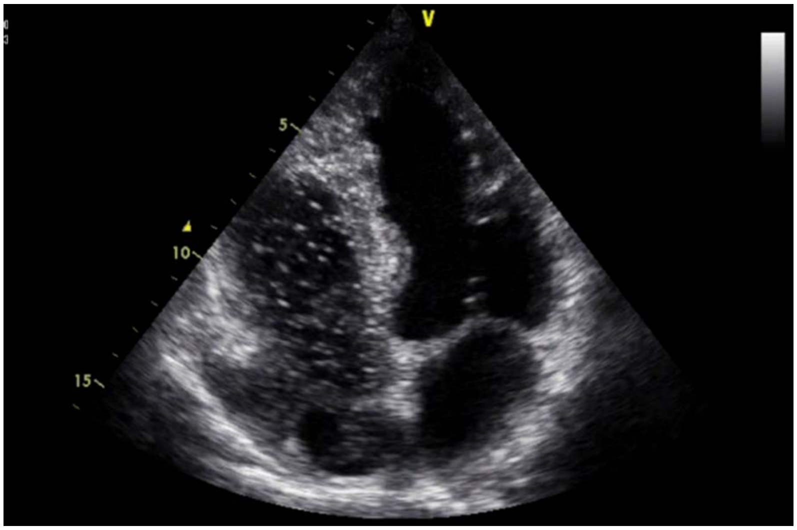


Figure 6. Still image of a heart with high grade venous gas emboli in the right heart (visible on the left side of the screen, captured during two-dimensional ultrasonic imaging (see Figure 5).

Rules that Should Be Flexible

There are times when over-applying well-intended rules can get in the way of safety. For example, divers are frequently trained to surface with a reserve in their tanks. If the concern for surfacing with this reserve intact becomes so compelling that stops, either required or deemed appropriate based on events during the dive, are abbreviated, the rule becomes counterproductive. Dives should plan to surface with a gas reserve, but using some of that supply to extend stop time for prudence may be appropriate.

Another area where safety can be compromised by good intention involves reverse dive profiles. If all other things are equal, planning the deepest dive first makes sense in that it is consistent with good practice for inert gas management of multi-level diving. But all things are frequently not equal and there is no evidence that the body registers whether inert gas accumulates at a given pressure. The important thing is the total accumulation and the subsequent driving pressures to eliminate it from the body. Practically speaking, the order of the maximum depth between two dives can be unimportant. Concerns arise when the 'deepest dive first' rule is applied with such rigor that an unnecessary deep dive is conducted for no reason other than to "allow" a second deep dive when it must be scheduled later (for example, to meet a suitable tide state). Mindless fixation on rules can create problems. Dive planning should be thoughtful.

Surface intervals also need to be considered. There is a trend towards progressive shortening in some subgroups of the diving community, possibly aided by the permissiveness of dive computer algorithms. Surface intervals are important for inert gas elimination. The minimum reasonable surface interval will vary with the exposure, but exceeding the minimum remains good practice. If very short surface intervals are required, the severity of the dive profiles should be moderated where possible.

Flying after diving

The conclusion of a dive series may require consideration of appropriate surface intervals before flying after diving. Planning is often based on current guidelines produced in a 2002 workshop (Sheffield and Vann 2004). The recommended minimum pre-flight surface intervals were developed from the available data, much collected in a 20-year study conducted at Duke University, funded by both DAN and the US Navy. In summary: 12 h after single dives within no-decompression limits dives; 18 hours after multiple dives per day or multiple diving days; and "substantially longer" than 18 h after decompression dives. The recommendation pertaining to decompression diving was vague in recognition of the limited available data. A minimum preflight surface interval target of 24 h remains good practice, and it would optimally follow a conservative final day of diving. The latter can be achieved by conservative profiles, and, for rebreather divers in particular, prolonged periods of high PO_2 breathing to clear inert gas at the end of final dives.

An additional consideration for the current flying after diving guidelines is that they apply only to aircraft cabin pressures equivalent to altitudes in the 2,000-8,000 ft (610-2,438 m) range. Exposures of less than 2,000 ft were excluded from consideration. Those wishing to compute exposure limits for less altitude exposures can refer to US Navy tables, which describe the threshold for altitude exposure at 1,000 ft (300 m) (USN 2008). Exposure to cabin pressures equivalent to altitudes above 8,000 ft cannot be guaranteed prior to flight, for example, for cases in which cabin depressurization occurs. For this reason, conservative decision making for flying after diving is warranted.

Conclusions

Ultimately, the best way to protect divers is to build conservatism into all elements. The net effect can be a high level of safety, often with relatively little compromise in the dives that can be completed. When awareness and good practice are maintained, even untoward events can often be effectively managed. It is most critical that divers understand the why of rules rather than just the rules. This allows them to be a critical piece in determining safe outcomes.

References

Pollock NW. Factors in decompression stress. In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Wrigley Marine Science Center, Catalina Island, CA; 2016; 141-158

Sheffield P, Vann RD, eds. DAN Flying After Diving Workshop Proceedings. Durham, NC: Divers Alert Network, 2004.

US Navy Diving Manual, Volume 2, Revision 6. NAVSEA 0910-LP-106-0957. Naval Sea Systems Command: Washington, DC, 2008: Chapter 9.

QUESTIONS AND DISCUSSION

AUDIENCE MEMBER: How do the visual signals correlate with aural Doppler measures?

NEAL POLLOCK: Imperfectly, but definitely conceptually. The IVa using current transthoracic echo (TTE) imaging scales falls in the range of a grade III using the aural Spencer scale. We compared the two for a while, but most labs are replacing the old aural technology if they can afford the TTE systems. They are expensive machines; on the order of $70,000^{US} for a GE Vivid q, but they provide great sensitivity.

RICHARD PYLE: If I understand correctly, it is more interesting to not look at the gradient factor, but what the diver was actually doing in terms of the profile pattern.

NEAL POLLOCK: Yes, but for the practical side we have guidance with the gradient factor if divers come close to following the ceiling.

RICHARD PYLE: It seems like when you are reviewing these, I am looking less at the gradient factor numbers and more looking at the shape of the dive profile. That seems like more telling the story.

NEAL POLLOCK: Yes, but the two come close to coinciding in some cases.

SIMON MITCHELL: I think the gradient factor number that you can look at is the high one.

NEAL POLLOCK: Yes, it is generally more meaningful.

SIMON MITCHELL: So that one is a little bit more meaningful than the low one in these profiles because if they are not following the ascent profile absolutely it is not really a validation.

RICHARD PYLE: Right.

DOUG KESLING: What would be interesting would be to measure the distance between the ceiling and what they actually did in the profile and quantify that.

NEAL POLLOCK: As a real gradient factor, not what they are setting as a gradient factor.

DOUG KESLING: That is right. And see what the margin is there and how close they are approaching and looking at that statistically.

GREG McFALL: Do you have the opportunity in these studies to follow the same person?

NEAL POLLOCK: Yes. When someone participates in one of these research studies, often part of week-long events, we follow them after every dive once they commit to the program. A substantial number have also participated in multiple study periods.

GREG McFALL: Do you ask them to change their gradient records on subsequent dives?

NEAL POLLOCK: These are observational studies. We do not ask them to change their activity or practice. We do share the information we get in real time. They can choose to do with it what they will. It is not uncommon for them to change their gradient factors after surfacing with high bubble grades.

GREG McFALL: What if they volunteer to do that?

PHIL SHORT: I participated in these studies over the last five years in Grand Cayman, I had a habit of bubbling quite heavily but then getting rid of those bubbles quite quickly. Wetsuit down to the waist and I have an initial habit of bubbling quite aggressively. Then an hour later, dry, back on shore, less than a couple hours, all gone. Every day I was doing a morning deep dive to 300-330 ft (90-100 m), and then in the afternoon to 200 ft (60 m) for six days in a row. And I was tweaking my numbers every time and getting results of low bubble scores as a result of that. We did that year after year.

NEAL POLLOCK: To address another question, someone asked whether you should you tailor your gradient factors for given dives. What are you running now?

PHIL SHORT: This conference has interested me because I am running 20/85 and that is as a result of the tests I did with Neal. I feel good after dives with that. With other gradient factors, I do not feel so good. I feel stretched, tired, et cetera, but I have never been bent.

NEAL POLLOCK: What are other people using?

RICHARD PYLE: We use 30/70 on the Shearwaters. DCAP does not let us change anything. That is what raised my comment about what the computer is set to not being correlated with ascent profiles. On the NOAA cruises with blue water ascents, they are much closer. When we are diving drop-offs, there is lots of science to be done on the way up. So if you look at how quickly we approach our ceilings, it is usually a pretty big gap on this. So the gradient factor, certainly the first number, is almost irrelevant.

GREG McFALL: As a rule, we have been diving 30/85.

NEAL POLLOCK: So 30/85 for the NOAA folks. Is that a dictated number?

GREG McFALL: No. It was the default. We have been diving that for many years and, knock on wood, have not had any trouble. But it would be interesting. And the reason why I ask you if they can change settings is not to go towards the less conservative end of the spectrum, but if you are bubbling at 35 and then adjust that to make it more conservative and you see a reduction or an elimination of them, it would be nice to find a more conservative instead of just presuming that it is going to be.

NEAL POLLOCK: Absolutely. Anybody in the studies can change their numbers. Phil is a good example. He very quietly did that for a long time, tweaking every day and seeing what he could come up with. He always had that smile on his face, and would go back and add some notes and make other changes. The people who participate can often get useful insights. Some will find out that they tend not to bubble, others that they bubble a lot. Many use the information to change their practice. Some take advantage to try different techniques. We had one individual who tended to have zeros most of the time, but on one dive was working harder than normal on the bottom and came up with transient high-grade bubbles. Such information can be useful. But you cannot say that making uniform change is necessary for all individuals.

SIMON MITCHELL: Neal, just to put some perspective on some of these numbers being batted around in terms of gradient factors. If you ask a bubble model what it prescribed for the same dives and then interpreted it in terms of gradient factors, it would look more like is 10/125. Those kind of numbers are what a bubble model will spit out. It will impose more deep stops with the expectation that that will enable you to do less shallow stops. So you surface with a very high gradient factor.

RICHARD PYLE: I think you were alluding to this. Has anyone tried to reverse engineer whatever mathematical algorithm you need to say, here is an actual dive profile. What gradient factors would produce this?

NEAL POLLOCK: Yes, you can. Martin Parker said that he can do it now with his software. We have been trying to do it ourselves. The problem we run into is manpower. It is not that mathematically difficult to do as long as you have the time to make it happen.

RICHARD PYLE: Time to write the code or time to manipulate every single profile?

NEAL POLLOCK: To write, test, and implement.

In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of
NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Durham, NC; 2016.

CONSENSUS DISCUSSION

Editors' Note: The following text was extracted from a transcript of the meeting provided by a court reporter. Editorial changes were made to correct grammar and remove extraneous comments. Reference citations were added where key to the narrative. Every effort was made throughout to retain the spirit and intent of the original discussion. The recommendations appearing in the front of this publication reflect the final form generated after review of draft materials circulated electronically to participants.

NEAL POLLOCK: Thanks, everybody, for coming. Welcome to the Rebreathers and Scientific Diving Workshop. I am one of the three individuals that were put on point for this. It is really Steve Sellers who pushed this concept, adding me and Jeff Godfrey to help in the effort.

--- short break in recording

AUDIENCE MEMBER: We are diving oxygen rebreathers and our main issue is O_2 toxicity. We do not have any sensors in our loops but we assume 98% oxygen at 20 ft (6 m) to give you basically that 1.6 ATA and a 45 min limit on any one dive, but we rarely actually spend all our time at 20 ft (6 m). We are mostly running at around 10 ft (3 m). Do you think that we should be concerned with that 45 min limit? This is our debate within our group.

NEAL POLLOCK: Do you have anyone who has had problems?

AUDIENCE MEMBER: Again, your whole point was perfect because we have some young, new divers coming in who have seen these tables and ask if we should be limiting ourselves to a single 45 min dive. Then we have got some old people like me saying, I have done 200 dives on these things and never had any trouble. And the unit is built for three hours. The Navy says there is a 240 min limit that they do not put on any single dive, but accept as a daily limit. The Navy, when we trained on them, said you can put four hours and you can do it all at once if you want. We are trying to figure out what the physiology is and why we need to stick with one versus another.

NEAL POLLOCK: It seems that the O_2 is less of an issue if you are not having any problems - no coughing, no symptoms, particularly since you are running below your limits. If you calculate based on your actual exposure you would probably see you were under the exposure limit. Simon, what do you think?

SIMON MITCHELL: I think that what you are doing is more important than what the absolute limits are because that has a huge influence on oxygen toxicity because of the CO_2 issues I was talking about. In other words, if you are exercising hard --

AUDIENCE MEMBER: Which we do a lot.

SIMON MITCHELL: You do? I think that that probably indicates a need to err on the conservative side. I agree with Neal's earlier comment that you have got to have something you can teach people because we do know that oxygen exposure is an issue even though we are not quite sure how to handle it. And over the years the NOAA limits have formed a very nice basis, albeit one that we are not entirely sure about being valid. There are a lot of reasons to think they may not be valid. But they do form a basis for discussion and practice. But there is an overlay on it all, which is what are you doing when you are exposing yourself to oxygen close to the limits. Typical divers go over these limits by 200-300% all the time during deco when they are not exercising. And actually, I think that is a relatively safe thing to do because they are not retaining CO_2. Their risk of a seizure is pretty low. Sitting at deco breathing 1.4 ATA O_2 at rest without CO_2 retention is probably safe. It is very contextualized. It is hard to give you an answer.

AUDIENCE MEMBER: The other question is whether we should put O_2 sensors in our unit, at least in a testing way. When we are on these units, we are actually dumping nitrogen all the time. Our concentration is actually dropping during the dive.

NEAL POLLOCK: But most of that flushes early.

AUDIENCE MEMBER: We do a three-breath flush, but then theoretically we are still dumping nitrogen because you have a high oxygen pressure.

SIMON MITCHELL: It would be a small amount of gas. I do not think adding the complexity of an oxygen cell is worthwhile.

AUDIENCE MEMBER: Not that we would need it permanently, but just as a test to know where we are running ourselves.

DOUG KESLING: You could run it on a computer and let it track. It is not going to be in a loop, but you could monitor your CNS exposure on a self-contained computer.

NEAL POLLOCK: They are interested in getting the exact loop concentration during normal activity.

DOUG KESLING: But not getting the additional monitoring equipment, a simple solution would be to slap on a wrist computer, make it closed-circuit for oxygen and let that track your CNS or UPT.

KARL HUGGINS: Are you able to find any that would go over 50 that are relatively inexpensive?

NEAL POLLOCK: Now you are asking for a lot.

AUDIENCE MEMBER: I have a question about CO_2 retention. If we are on a high O_2 concentration in shallow water, is that even with exercise?

SIMON MITCHELL: Actually, we will be in a better position to answer that question in the near future. We ran a study last year where we measured end-tidal CO_2 concentrations on rebreather divers surfacing after resting decompression to reassure ourselves that there was no evidence of CO_2 retention when you are resting on deco breathing on a rebreather. We found no evidence for a general trend to retain CO_2. We are going to repeat that study in Australian Navy tech swimming divers on training dives. They will be swimming flat out at 3-6 m (10-20 ft) on oxygen rebreathers. We are going to measure their end-tidal CO_2 the second they hit the surface at the end of those training dives, essentially repeating the earlier study. Later this year I will be in a position to answer that question for you. But at the moment I do not think anyone has done that.

AUDIENCE MEMBER: What units are they using?

SIMON MITCHELL: LAR Vs.

RICHARD PYLE: I have talked to Simon about this but I want to ask other people in the room if they are aware of anything. The same context of data versus evidence and that sort of thing. Imagine an experiment where you put two divers in a chamber. One of them is breathing air and one of them is breathing pure O_2 at a simulated depth of 60 ft (18 m) or whatever depth can be used. They both sit at rest for three hours. You then put them both on exercise bikes both breathing oxygen at the same depth. Is one more likely to seize than the other? Now, I know what the intuitive answer is. Obviously, the guy who is been breathing oxygen a long time intuitively is more likely to seize. But are there any data to actually show this? In other words, is there anything supporting the cumulative O_2 exposure effect on CNS toxicity?

NEAL POLLOCK: You have got anecdotal reports and expectations that would make this a difficult study ethically.

RICHARD PYLE: The Navy has never --

NEAL POLLOCK: The Navy did some O_2 tolerance tests.

RICHARD PYLE: Right. And it is my recollection looking at those graphs, they are shotgun blasts, correct?

NEAL POLLOCK: Yes.

RICHARD PYLE: But, but the point being that there is not much of a correlation between prior exposure of oxygen and propensity to seize. So that is the entire basis of the CNS clock conceptually? Is there any actual data to support the fundamental premise?

NEAL POLLOCK: Well, we know that you do not see patients resting in a hyperbaric chamber at 2.8 ATA seizing and that prolonged exposures like this for an immersed, let alone exercising diver would be very risky.

RICHARD PYLE: But if Simon says the real issue is probably CO_2, what distinguishes in-water scenarios; the breathing apparatus? What I am trying to get at is that a lot the computers and a lot of training follows the CNS percent concept, which, as Simon has already said, is routinely blown by 200-300%. I accept in the one sense that, yes, you have to start with something, but there ought to be some reality to the something. We do not have a helium clock. And the reason we do not have a helium clock is we have no data to support that there is any reason we should consider a helium clock. And my question is whether we have any data to support any reason for thinking we should have a CNS O_2 exposure clock?

KARL HUGGINS: Correct me if I am wrong, but I have not seen anything that has taken the percent calculations for the O_2 clock and actually done any tests on it. I have not found anything in my searching that has actually said, yes, this amount of time, this depth, is equal to the same percent risk of this amount of time at this depth. As far as I know, it is just hand waving mathematics.

RICHARD PYLE: I am going one level lower. Is even the basic premise valid?

NEAL POLLOCK: I think you have to say the premise is valid. Your resting subjects are not having a problem. Exercising subjects are.

RICHARD PYLE: No, no, no. That is the premise of CO_2's contribution to seizures. What I am talking about is the cumulative exposure of oxygen increasing propensity. If you flip a coin 20 times and it comes up head every time, the 21st time it is still 50/50 whether it is going to be head or tails.

NEAL POLLOCK: I do not have the answer but I expect that the risk is higher with more background loading. It would be an interesting study, but challenging to get past an ethics review.

RICHARD PYLE: But, I mean, we have some theoretical reasons to assume that there is a cumulative effect of oxygen exposure that will increase your propensity to a seizure later whether you are exercising, whether you are resting, whatever. My point is diving a rebreather at 1.6 ATA for three hours and then fighting a current on deco at 1.6 ATA. Would it have been better if I had a 1.0 ATA for the three-hour part of the dive? I think there is no data to even suggest one way or the other that I am more likely to seize having had the history of oxygen exposure, which is what the entire CNS clock concept is based on. It is intuitive, not data based.

NEAL POLLOCK: Intuitively, I would think the risk is higher.

RICHARD PYLE: Very intuitive and there is even anecdote, but I see no real data to support.

SIMON MITCHELL: Neal, just give me five minutes. I am trying to find Dick Vann's paper from the tech diving workshop.

LIZ KINTZING: I have seen two people seize in chambers at 60 ft (18 m). I thought you said they did not.

NEAL POLLOCK: I overstated the situation; seizures are not common during HBO therapy despite the high PO_2. Certainly not at the frequency you might expect during immersed exercise with the same PO_2. I did not mean to imply that it never happens.

RICHARD PYLE: While Simon is looking it up, I kind of botched that hypothetical experiment. Let us say two divers, three hours, one is exposed to a high PO_2. One is exposed to a low PO_2. Whatever work-rest conditions. Then after that three or five-hour period you expose them both to the same high PO_2. And exercise or not exercise, whatever. Does one of those two divers have a higher likelihood of seizure? The premise of the CNS clock says yes, the guy with the higher previous exposure. But I do not know, and I have been looking really hard to find any data to support this belief. It seems like we ought to know before we start building all these limits based on CNS clocks.

AUDIENCE MEMBER: I want to say there was something anecdotal about O_2 spikes in that it seems like there is a greater prevalence of oxygen toxicity on open-circuit technical dives. And it seems like a lot of the onset happens from the gas switches from low PO_2 to high PO_2. I remember reading that somewhere. It was a question that was presented in favor of rebreathers with constant PO_2s.

AUDIENCE MEMBER: I did talk to Dr. Vann on the phone during our debates about this and described our general diving patterns. His reaction was you guys are so far away from the limits I would not worry about it. Would it be useful that we have got thousands of dives on oxygen rebreathers that go for different stretches of time and we have never had anybody have a hit?

NEAL POLLOCK: It would useful to document and report.

DAVE CONLIN: Rich, the other thing you can do is put people in a chamber on pure oxygen at 30 ft (9 m) and just wait until their CNS percentage went to 100, 200, or 300%. I would be very surprised if people started toxing when they hit 100% on the CNS clock.

RICHARD PYLE: I think that is well established. There is no magic wall you are going to run into and suddenly get a spike in probability of seizing. The problem is if you do a simple experiment like that where everybody is exposed to oxygen, most of the experiments they turn at the point of seizure. By definition, the more minutes you are exposed to that, each minute has an equal probability of a seizure. You see what I am saying? So the question is, is that 300th minute, are you more likely to seize during that minute than you were during the first minute or the 10th minute or the 50th minute.

KARL HUGGINS: The only thing I have been able to find is the Harabin et al. (1995). They ran 688 trials with 42 exposure-stopping symptoms, and found that the model predicts the probability of oxygen toxicity to be less than seven percent with current Navy limits while breathing 95% oxygen.

> *Harabin AL1, Survanshi SS, Homer LD. A model for predicting central nervous system oxygen toxicity from hyperbaric oxygen exposures in humans. Toxicol Appl Pharmacol. 1995 May;132(1):19-26.*

RICHARD PYLE: Does that specifically say that there is a cumulative effect?

KARL HUGGINS: I have to pull up the full article for that.

RICHARD PYLE: I apologize for burning so much time on this. It is just that everyone presumes there is an established scientific basis for the fundamental notion of CNS percent. I wanted to learn if I have been missing something.

AUDIENCE MEMBER: That has also been my issue. I have not seen it either. I am trying to make an argument but cannot because I am not an expert at it.

RICHARD PYLE: Training agencies assume it. We in the scientific diving community assume it. NOAA assumes it. All plausible assumptions, but there are a lot of things I have learned over the years where the obvious was not so obvious after all and the intuition did not pan out. It would be nice to pin this one down. Maybe it is too impractical to run an experiment on humans. You could run it on rats or something else.

NEAL POLLOCK: The animal model would likely not translate too well.

DAVE PENCE: Just taking this group of experienced DSOs and rebreather divers, how many of you are in programs where the program absolutely requires a strict adherence to a CNS percent no greater than 100%? A lot of manuals say, you will not go above the US Navy/NOAA either the CNS percent limit or the NOAA limit. How many of us truly abide by that absolutely? You have never run a PO_2 of 1.6 ATA for longer than 45 min or a PO_2 of 1.3 ATA for longer than 120 min? Is there anyone in the room who has not done that? Let the record show that no one raised their hands to say they absolutely adhere to the NOAA single exposure limits.

DAVE PENCE: I think that does raise a question as we have a set of numbers labelled as limits as opposed to guidelines. And we as a community are not accepting what is defined as a limit within our own practice. We need to, as a group, very defensively recognize that and affirm that, while still recognizing that there are certain legitimate risks to high oxygen exposure that have to be managed. It is an area that I think, from a liability standpoint if nothing else, needs to be addressed.

NEAL POLLOCK: Good points. A measured approach is required. I do not think it should be thrown out completely from the awareness point of view, even if numerically it needs work.

RICHARD PYLE: I believe it was Bill Hamilton who came up with the CNS exposure limits. And I had this conversation with him while he was still alive and pinned him down to it and finally got him to confess that it just made sense at the time.

DAVE PENCE: Along those same lines, is there anyone in the room who has a true understanding of the history of where the NOAA limits came from? My casual conversation with Morgan Wells at one point is that it was sitting in a room curve fitting things that did not have a lot of data other than maybe 45 min at 1.0 ATA for 300 min based upon vague chamber exposure.

RICHARD PYLE: That is consistent with my conversation with Bill Hamilton about exactly that question.

KARL HUGGINS: Even if you look at Donald's work where he summarized his work after Ed Lamphier did his work with the Navy, there is this huge argument he has on Lamphier's limit on mixed gas oxygen limits. So there does not seem to be any type of agreement between the two people who did a lot of the early work in trying to set up the limits.

SIMON MITCHELL: Dick Vann's description of the prominence of the limits sounds like this: "These limits were based on best judgment from extensive experience, not on the statistical analysis of quantitative data."

AUDIENCE MEMBER: That is for these NOAA limits?

SIMON MITCHELL: Correct. These notes were based on best judgment from extensive experience, not on statistical analysis.

RICHARD PYLE: In their defense, you have to start somewhere. It is just we are at a maturation point in our community; we now have the hindsight of empirical experience. Maybe we should reevaluate some of these things where they had nothing to go on other than a best hunch and moving forward.

NEAL POLLOCK: This is where documentation is critical. Reporting extensive experience with safe exposures beyond the established limits would be useful.

AUDIENCE MEMBER: That is what I talked to Dr. Vann about. Our only limitation is we actually never know what our loop has. If we could at least do some typical run with measuring what the loop is, then we might be able to at least say in a general sense.

SIMON MITCHELL: There is another pertinent comment from Dick Vann in his paper: Because the data on which the model was based were practically nonexistent at least for low partial pressures all that can be stated about the limits of Table 1, that is the NOAA limits, is that the risks of CNS oxygen toxicity are probably small. It refers again to nonexistent data.

DAVE CONLIN: For those of you who did not see Steve Sellers' AAUS presentation about our institutional reaction to the dive accident that we had, the fundamental problem is we as experienced divers can get together in a room and agree that there is a lot of latitude in the percent CNS, but the truth of the matter is that the people who are going to be passing judgment and making decisions about these things are not the people in this room. They may have little to no understanding of diving or the subtleties of diving. They are going to go, it says here that you need to X, and you did Y. So maybe what we need to do is sit in a room and based on our experience come up with something.

NEAL POLLOCK: The way to approach something like this is to identify it as a community priority and then generate some data. Evidence-driven advancement. And so that is the way to do this. Messy data is a starting point. Someone else puts a brick in the wall. And if it needs it, you have a half-day symposium or two-hour session to present the data and then to come up with a consensus guideline. We need the data.

JIM HAYWARD: Rich, you have got a database of your dives and all that. Cannot you pull up and find out exactly --

RICHARD PYLE: That is why I was raising my hand. The answer is yes, and we can. And I have not done that analysis. When I am working with Poseidon on it, I will certainly do it from my own dive profiles. But I want to go beyond that. I do not want to limit it just to Poseidon divers. I would like to come up with a mechanism for aggregating. If we can aggregate all this raw data, then we can start -- they are not controlled studies. So it is not the precise profiles and exactly the control you want. But when you get a large enough dataset, we can start to statistically pull these patterns out even without the controls. Because the control of it spreads out evenly over the breadth of all of the variations going on. Thank you, Jim. We have a pathway to answer this. That was my whole point about data as being the big, number one next step in rebreather evolution.

NEAL POLLOCK: The best way to do something like this is to make it a community priority and set a timeline to develop, present and publish. That would then provide the administrators with more evidence. You can start with the Poseidon platform and know that others with the same capability would probably contribute so they were not left behind.

RICHARD PYLE: I have got Shearwater logs from a bunch of places. I have got Mark V logs. Whoever has the data, which is basically if you have got a dive profile that includes depth and PO_2, we can probably start to hammer out these things quantitatively. We can start looking at when you ended the dive, what was your CNS percent according to the model and we can start to see what is actually happening out there in the world.

NEAL POLLOCK: One of the important things we are back to is data reporting. It is shocking how little information is often provided in incident reports coming to AAUS. We need to do a lot better with comprehensive reporting. This should start with dive records. Electronic profiles are frequently recorded, but we need to do a better job in collecting them. Why not submit them as a regular requirement. They could be useful in many ways. The CNS percent question is a straightforward one. How many here collect electronic dive profiles in their programs?

DAVE PENCE: For rebreathers?

RICHARD PYLE: Or Shearwaters.

NEAL POLLOCK: Does not have to be rebreather.

LIZ KINTZING: Directly downloaded.

NEAL POLLOCK: So right there we could actually put together a fair bit of data.

RICHARD PYLE: That is exactly where I was hoping we could leave this. We can talk about this more during discussion.

KARL HUGGINS: The only thing I would hazard on this is ask for the data, but do not tell them what you are actually looking at. If you are looking at can we push these limits beyond what the NOAA limits are, I mean, they are doing it.

NEAL POLLOCK: Agreed. The collection should be matter of course, minimizing the possibility of bias. The best way is to draw from data collected with no prescribed purpose. If helpful, there is no reason why this could not be a mini workshop at an AAUS meeting.

RICHARD PYLE: This is what you and I and Dick have been talking about for years now. It would be great if we can use the scientific community.

AUDIENCE MEMBER: Do not you need a point of failure or a point of seizure in this case to set limits?

NEAL POLLOCK: Not necessarily. If you are referencing a hard line that exists on paper and we can show that X number of people are going X percent beyond that hard line without any problem there is justification to reconsider the limit, possibly establishing an interim value. Prospective research would probably be the next step is more tightly defining the most meaningful new limit.

DAVE PENCE: I also want to make sure that we are all clear that primarily what we are discussing right now is this limit is applied to seizures. Many of these lower PO_2 exposure guidelines may well be dealing with either pulmonary exposures -- personal experience hyperoxic induced myopia is a real thing.

NEAL POLLOCK: That is part of why we need better reporting of all adverse or meaningful events. Because, you are right, we have to look at what is going on.

RICHARD PYLE: If I could just reiterate, all of my verbiage before was purely focused on CNS. Pulmonary is a whole different issue. I want to make that clear to everybody that I was only focused on CNS symptoms.

NEAL POLLOCK: What we have accomplished so far is to complete about 15 hours of talk, very productively, hopefully bringing fresh ideas to many. Now we start the best practice discussion. It seems logical to complete it in three stages. We will start by developing a topic list from the participants. The ground rules for this session are important. This is not a discussion period. We want to identify issues, possibly getting clarification, but no discussion. We want to make a laundry list to be refined tonight into what we would call straw man statements. We will present these tomorrow in statement form for discussion by the group.

GREG McFALL: First, I would like to come to a consensus on when to recalibrate O_2 sensors. Second, when to change your scrubber. There needs to be some kind of guidelines on how long can you store it in what conditions. Third, how many CCRs can a person be proficient on? Fourth, the best practices for mixed teams. And five, best practices for team bailout.

PHIL LOBEL: Discussion on which units we can really use. I have heard a lot about ISO 9000 verifications. We see a lot of different units. Which are really qualified?

NEAL POLLOCK: Okay, third-party testing and approval requirements.

DAVE PENCE: Given changes in available equipment technology since our standard was last written, should certain additional elements of rebreather design be considered required.

NEAL POLLOCK: The fundamental need would be to update standards.

DAVE PENCE: Should an integrated open-circuit bailout mouthpiece be considered a required element in a rebreather? Should alarm systems that are separate from the monitoring system be required and should those alarm systems be detectable by all divers of a dive team without the active participation of the diver in question?

JOHN BRIGHT: How about AAUS training standards.

NEAL POLLOCK: Okay, update equipment and training standards.

GREG McFALL: Depth progression. Once you get your 100 m (330 ft) certificate, does that mean that you should actually be working at 100 m?

NEAL POLLOCK: We can probably actually compound that and say independent operation and depth progression.

DAVE PENCE: Diver versus supervisor.

AUDIENCE MEMBER: Disinfection protocol.

AUDIENCE MEMBER: As a non-CCR identifier, what type of support I should offer and what type of things I should check when you guys come in to dive at a facility like this so that I am not putting unnecessary burdens on you. Perhaps a form or something that I could require the divers to give me that proves that they have checked stuff. They have come with a letter of reciprocity (LOR).

NEAL POLLOCK: So information for non-CCR support staff and administrative personnel.

PHIL LOBEL: A standardized form for reporting dives and for the database.

JEFF BOZANIC: When should workup dives be required or not necessary? A currency definition.

AUDIENCE MEMBER: Minimum dives.

RICHARD PYLE: Oxygen exposure limits, minimum setpoint, maximum setpoint.

AUDIENCE MEMBER: Crossover training requirements. Training for people with no open-circuit certification.

AUDIENCE MEMBER: Frequency of skill evaluation and rescue refresher dives.

AUDIENCE MEMBER: Outside of just workup dives, hearing that motor function is most important, how often are we going out and just practicing these skills over and over.

JEFF BOZANIC: Incident reporting for less serious incidents.

AUDIENCE MEMBER: O_2 handling in field situations when you are out on a boat.

NEAL POLLOCK: O_2 handling in field environments.

DAVE PENCE: Multi-institutional operations.

AUDIENCE MEMBER: Duration and acceptable level of negative tests. And how often are people doing positive tests?

NEAL POLLOCK: So positive and negative test guidance.

RICHARD PYLE: Prebreathe duration and purpose. Why we do prebreathes and how they should be done.

PHIL SHORT: Policy on modifying units outside of manufacturers' norms.

JEFF BOZANIC: Something about progressive checklist use.

NEAL POLLOCK: Build, pre-dive and pre-jump checklists. Iconography if that fits.

JEFF BOZANIC: When should they be required and when should they not be as necessary based on experience.

AUDIENCE MEMBER: Task loading progression and new environments progression.

AUDIENCE MEMBER: Do we want to tackle alterations?

NEAL POLLOCK: We have a draft statement there already: "Any rebreather modifications should be reviewed and approved by manufacturers." Discussion tomorrow.

DAVE PENCE: That is strong.

NEAL POLLOCK: Yes, but it will be open to debate.

RICHARD PYLE: To clarify, you might want to specify the scope of a modification. If I add an extra depth sensor on my wrist, am I modifying the rebreather? There is a continuum.

NEAL POLLOCK: Great point. My thinking is that our statements are to be fairly broad. The next step for many will be how to operationalize them. It will be great if refined details can be established for individual points.

AUDIENCE MEMBER: Entry level skill requirements.

STEVE SELLERS: Guardian angel requirements.

LIZ KINTZING: Days off, operational limits, accessing fatigue.

AUDIENCE MEMBER: Using different algorithms, whether it is on your backup computer should be different from your handset, pros and cons.

NEAL POLLOCK: How to review and approve algorithms.

JEFF BOZANIC: Approved absorbents. Many people consider using medical grade absorbents that have not been tested by manufacturers.

AUDIENCE MEMBER: The inclusion of gas density planning as a dive planning parameter.

JEFF BOZANIC: Recommendations on gas switches on deep dives.

AUDIENCE MEMBER: Standard on how to deal with an unconscious rebreather diver.

DAVE CONLIN: There is one already, is not there?

NEAL POLLOCK: Yes.

SIMON TALBOT: Recommendations on full face mask use under any circumstances.

LIZ KINTZING: And those neck things.

AUDIENCE MEMBER: I think the last question was the 40% rule, a question on that, 40% versus tank cleaning oxygen.

NEAL POLLOCK: We have oxygen safety. I think this is covered.

AUDIENCE MEMBER: In-water recompression?

MARTIN McCAFFERTY: This really does not belong on the list, but I just want to remind everybody that comment about in-water recompression, please, all of you, and forgive me, this is kind of selfish on my point because I will be dealing with the aftermath, as you go through these discussions, please be very careful about posting this stuff on social media. You have recreational technical divers that grab these things out of context, out of where they should be, and start spreading these things amongst themselves. So I am not saying do not do it. Just be very weary. I have got cornered on way too many in-water recompression arguments, so that kind of subject. So please be mindful of that in how you use it.

AUDIENCE MEMBER: CCR accident form that everybody would use the same form.

DOUG KESLING: I would go one further and say maybe an accident/incident kind of chain of command custody guideline on how to deal with equipment and stabilization.

AUDIENCE MEMBER: Tailgating on that dive log forms, standardization, what to include.

AUDIENCE MEMBER: You want to throw the database in here?

RICHARD PYLE: Is that a discussion point or is that something we are just going to do?

NEAL POLLOCK: That is something we are probably just going to do.

JEFF BOZANIC: Some definition of how often these statements or standards ought to be reviewed in the future so that we know that we come back to this in a certain period of time to re-evaluate.

NEAL POLLOCK: So, best by date for best practices, okay.

GREG McFALL: This should not go on this list but are we going to come up with some kind of disclaimer that we are agreeing this is what is right for our community, not necessarily for the recreational community.

NEAL POLLOCK: We can include an appropriate disclaimer. These are going to be in the proceedings of this meeting as recommendations for best practice guidelines. We will not use the word regulation or rule.

There can be language indicating that this came out in consensus discussion with this body, but is not intended to be definitive. They are points of reference that will undoubtedly require further consideration.

GREG McFALL: For the way we need to dive.

NEAL POLLOCK: Our effort is focused on the scientific community. Having said that, a lot of the recommendations that come out may well apply beyond this community. I think it is appropriate to state the intention of this group, but to stop short of saying that the product is exclusive.

AUDIENCE MEMBER: There are a number of items on the list that are exclusively stated in the manufacturer's guide, the service manual, like on approved absorbents or whatever you want to call it. I feel the statement for a number of these items is per manufacturer's recommendations.

NEAL POLLOCK: That is perfectly fine. Remember, this is the laundry list. Not all of these are going to stay in and for some the recommendation might very appropriately be to follow manufacturer guidelines.

STEVE SELLERS: Diver tracking for the onsite surface support.

AUDIENCE MEMBER: Do you want to make any kind of statement for the manufacturers in terms of what you are looking for.

NEAL POLLOCK: Presumably for any statement made, the manufacturers could look at and agree, disagree, or debate. I do not think we are trying to use a heavy hand, but to advance the common ground and stimulate further advancement.

RICHARD PYLE: I think Dave Pence already covered this one, but the notion that technology is evolving, so a best practice for standards is to develop them with the awareness that technology is changing and not to corner yourself. Was that the point you were trying to make, Dave?

DAVE PENCE: Bottom line is that there are things that are essentially becoming a regular community use item now that simply did not exist when the standards were written. For example, bailout valves which are now available from many different manufacturers.

SIMON TALBOT: Do we want anything in there specifically to address new technology that might come up on clearing the CO_2 sensors?

RICHARD PYLE: Generalize it to CO_2 monitoring.

AUDIENCE MEMBER: Requirements or guidelines for top-side support and safety divers and decompression diving.

NEAL POLLOCK: It sounds like we have a good initial list to consider. Time to get into the discussion.

DAVE PENCE: Neal, a question of process. Will the straw man essentially be a statement for consideration, positive versus negative?

NEAL POLLOCK: Statements will reflect input, and the group can accept, modify, reject or table each. Nothing is written in stone but the hope is that the effort will direct and speed the debate.

AUDIENCE MEMBER: Maybe testing protocols for the independent agencies that test these things that are more realistic to how the units are used.

NEAL POLLOCK: Now you are talking credentialing of third-party testing facilities, something like that?

AUDIENCE MEMBER: What I understand is that many people have problems with protocols that the units are put through for testing.

JEFF BOZANIC: One example of that is that everybody tests CO_2 absorbents at 39°F (4°C) and a workload represented by 1.6 liters per minute CO_2, and none of us dive that way. The test result is not directly relatable to the kind of diving that we do.

AUDIENCE MEMBER: But they are relatable to each other.

NEAL POLLOCK: So unit testing requirements.

DAVE CONLIN: Are we going to try and sort these out, all of us in the same room on all items, or are we going to break it out as subgroups?

NEAL POLLOCK: We do not have enough time to do the breakout and come back together. What we are going to try to do is present an initial list to see where we have easy agreement. You cannot really have a consensus with a panel of 50 people if you are breaking down into small groups unless you have time to fully inform everyone when they come back together. It would be unwieldy. We have to trust that in our mix of things we have some that are pretty straightforward to accept, others reasonable to modify or reject, and some that we may need to table. The effort should be worthwhile on a number of levels. If one of the things that we get is a number of things that we cannot reconcile right now, that may be useful.

DAVE PENCE: Straw man statement. We recognize that the ultimate responsibility and authority for the approval of the diving and the units rests with the institutional control board. That would just be the straw man. We can tear it apart. It says that in our manual.

STEVE SELLERS: How about the maximum depth question, maximum depth for rebreather use.

NEAL POLLOCK: Maximum depth for rebreathers. This is how the CNS O_2 toxicity rule got started.

STEVE SELLERS: I am just throwing it on the wall.

JEFF BOZANIC: Recategorization of deeper dives for reporting for rebreather usage.

NEAL POLLOCK: Let us start with a couple of soft ones and test the process. Here is the first one. Off-nominal incidents should be fully documented and, where possible, the information should be shared with the broader community.

AUDIENCE MEMBER: My Canadian is a little rusty. Can you explain what off-nominal is?

GREG McFALL: How about all nominal.

NEAL POLLOCK: Nominal is good. Off-nominal is bad. Okay, it seems the language has to change.

RICHARD PYLE: How about just incidents and then you have to define what an incident is.

NEAL POLLOCK: The reason I thought off nominal, some of those are pretty subtle and it just seems to me that maybe that is not a bad way to phrase it, but it is not necessarily a bad thing. It is not a bad incident. It is off nominal. If they are discussed and documented, they are around for the training purposes of other people. That was my logic. I am flexible.

DAVE PENCE: My only concern is how broad the term off-nominal incident becomes partly because, honestly, I would have to write an essay on almost every dive I do and so would most of my divers.

NEAL POLLOCK: Where should we cap this or should we have it at all? We have one call for possibly near miss.

JOHN BRIGHT: Incidents that could be teachable to the wider community. At the discretion of the dive supervisor or the DSO, off-nominal incidents are things that happen that are above the mundane. Like a partially leaking mouthpiece that causes a partial loop flood might not be something that needs to be reported over and over and over again, but incidents that happen that could have a particular value.

NEAL POLLOCK: This is actually why I had "documented" because I am not necessarily saying this has to be a big deal. But to me, when off-nominal things happen, you do keep track and if you start to see patterns, then it gets addressed with an educational update or a directive. That was my view.

JAMES NIMZ: I think we should stick to the wording that is in the greater safety community like they said near miss or fatal incidents.

AUDIENCE MEMBER: Worthy of documentation.

DAVE CONLIN: What if we just substituted "teachable moments" for "off-nominal incidents." There are positive things that people do that are smart that could be shared.

RICHARD PYLE: I think a point of clarity is everybody agrees with the concept. We are just quibbling over the words.

JEFF BOZANIC: Part of what we are all looking at here too is that all of us know that this is going to mean more paperwork for all of us. If we could establish something that made the reporting of this fairly easy and painless, then we might be more positively receptive to the concept as well. I am not sure how that would happen. I like the concept, but the question is how broadly are we going to interpret it? If we want to get data on all the little, minor incidents that go on so we can now have changed standards or changed design or change the way we practice -- for example, somebody did not open a mouthpiece fully. If that happens 18 times in your program over the next month, we would like to have that data, but not if it is going to cost us all 28 hours at the desk trying to write this stuff up.

NEAL POLLOCK: On the one hand, for this panel I get the sense that we should try to keep the higher practice hat on. What I would see as an immediate substitution is "where appropriate." It may be that the only thing you do is you keep track in your own office that there are a bunch of people having trouble with X. I am not sure this necessarily has to be a huge paperwork nightmare. It is a concept though.

JIM HAYWARD: How do you think it is being shared with the broader community? Are you thinking AAUS?

NEAL POLLOCK: Certainly it could be internal. It could be through AAUS. It could be through an incident report on an online reporting system. There are a lot of ways this could be addressed. The way I see it is if you have enough cases that they rise to the point that you see it as something of an issue. I am not sure that everything we would say here has to be a huge paperwork nightmare. It might be broad enough to manage. Just before you say that.

PHIL LOBEL: Could this be accomplished as a post-dive checklist? We have pre-dive checklists. Certainly post-dive we record our things. It is sort of going through, did everything work as functional. Rather than keeping it as an essay, just having it as a post-dive checklist where we are documenting that everything did or did not function.

JEFF BOZANIC: That is actually where I was going. If this were a simple form, mouthpiece problem explain, just a couple things we just have to go and check some items off at the end, it would not be a big deal.

NEAL POLLOCK: That would have to be all you would have to do. To meet the spirit of this, something like a checklist might be perfectly valid.

JEFF BOZANIC: Post-dive checklist is usually for cleaning a rebreather. This would be a post-dive incident reporting or a dive project summary review. The point is to try to make it easy so we can capture the data.

NEAL POLLOCK: I will tell you what. Let us leave this. I think we have had the discussion. Let us just be careful because we do have to be mindful of the time we have available. So let us leave this one for now and we will come back to it as we can. Research priority. Collect, review and publish data evaluating the efficacy and propriety of the CNS oxygen clock.

RICHARD PYLE: What do you mean by propriety?

NEAL POLLOCK: Appropriateness. We can say efficacy. So that would be fine. And I was really thinking and validity. Any issues?

DAVE PENCE: CNS clock and NOAA's oxygen exposure limits.

RICHARD PYLE: That is more complex than the clock itself.

NEAL POLLOCK: How about can I just say oxygen limits, CNS oxygen limits. Is that encompassing? What we do not want to do is make this so precise it becomes unhelpful.

DAVE PENCE: I would suggest you take out CNS. Oxygen limits, period.

NEAL POLLOCK: The reason is because of the difference in the pulmonary and the CNS.

DAVE PENCE: Exactly. We are dealing with prolonged exposures at moderate periods. We are just as interested in pulmonary exposures.

NEAL POLLOCK: Where are we on this? I have an okay from Liz. That means it has got to be good.

RICHARD PYLE: The way it is worded now could include what is our maximum setpoint. I do not know if you want to include that in the scope or if you are just talking about chronic exposure.

NEAL POLLOCK: In many ways it would be encompassed.

RICHARD PYLE: So setpoints would be included in this as well?

NEAL POLLOCK: It certainly can be.

JEFF BOZANIC: Could we add to this put in parentheses, including CNS limits, pulmonary limits, hyperoxic myopia and setpoint selection. That way we do not lose any of what we are all talking about.

RICHARD PYLE: Better to be more explicit.

NEAL POLLOCK: What I will say, if this more or less meets the group's sense, there may be a little bit of wordsmithing, but the nature of it is not going to change. Okay. So best practice guideline. The idea here, we have some things we have identified as research priorities. So we are saying effort has to be thrown at this. Collect, review, and publish data evaluating gas switch safety.

JEFF BOZANIC: Pretty straightforward.

NEAL POLLOCK: I am not hearing any nays. So, everybody was happy?

AUDIENCE MEMBER: I just want to clarify. You are talking about the gas, the safety issues with the gases, not the techniques?

NEAL POLLOCK: We are talking about the gases, the switch. We are not talking the process.

MAURITIUS BELL: I understood coming into this we were going to do best practices, but this is pretty large. And I feel there is already enough of a challenge collecting this data as it is. That is where we are a decent subset of rebreather users, we are not that large. How is this going to be done?

NEAL POLLOCK: Remember, these statements are not saying these are things that we have to do or individuals have to do. This is what is considered a statement for what is needed for best practice to know information. That is why it is a research priority. This is to try to get to a place where we can have best practices. We have to understand this issue.

SIMON MITCHELL: I just wonder, there are probably a few issues like this, Neal, where it may be possible to generate a useful, slightly directive statement at this point in time. You know what I mean. I think that is quite sort of wishy washy. And we will look at it in 10 years and go, yes, that would be good to do, but nobody will have done it.

NEAL POLLOCK: Okay. Simon, give us the words.

SIMON MITCHELL: There are a lot of people here trying to decide whether they should do gas switches. We could come up with a statement along the lines of, there is evidence that gas switching transiently raises inert gas pressures in the inner ear, and it is generally considered best modern practice to stay on your original diluent or something like that. Or, you know, we might include something like, while all gas switches are an accepted part of current practice -- just something that actually specifies practices. I think we have got as much as we are likely to have on this issue. I do not see us collecting any definitive data that is going to shed much more light on it. I am happy to take that one on and come up with a statement for tomorrow.

NEAL POLLOCK: We will work on some language. We will go through our list tomorrow to show the group where we are. For sure, if we can come up with something confident, that is fine. Everybody happy on this one for where it is right now? You will see this again tomorrow. This one is pretty short. Data collection should be increased. The idea here, and this wording could change, electronic dive records. We really do need those electronic dive profiles both for when things go wrong and when they do not, like things when the CNS on the clock comes up, would not it be nice to have those records?

RICHARD PYLE: This is probably going to happen anyway. Including that statement in a document probably makes it easier to get funding down the road to say, look, this group of scientists agreed this is something we need to do.

NEAL POLLOCK: We are not setting a timeframe, just saying that this should be done. Let us wordsmith this. We are coming very close to the end of the very short list we were able to put together today.

PHIL LOBEL: I think then we have to make recommendations to manufacturers. There has to be a standard format that the data is outputted and programs that can integrate that data. Because we all have dive computers that work at all different formats that we cannot easily collate.

NEAL POLLOCK: Actually, that is not strictly true. All the major dive manufacturers went to the DL7. So those records could be downloaded to DAN for Project Dive Exploration. There is actually a lot of commonality in the platforms already. From the computer point of view, it is not actually as bad. But for me it goes beyond just the computer too. We need the dive records that we are getting from the organizational members, for example, the AAUS members. How do we reword this?

KARL HUGGINS: Need to look at outcomes.

KARL HUGGINS: Some standard outcome categories.

JEFF BOZANIC: Do you want to include in any of these any concepts as to how we foresee something like this going on? Like when I see this it says, yes, that sounds good, but what does that mean. Does that mean should we have reporting to the institutions that then forward it on to AAUS? Does that mean to an individual diver should go to the website?

NEAL POLLOCK: So what does this mean? Is it reporting to the institution? Is it reporting to AAUS? Is it reporting to an independent website? That is a great point. To me it would be driven by AAUS.

JEFF BOZANIC: Or should this go to the manufacturers and say you guys are not capturing enough data.

RICHARD PYLE: It is kind of a tiered thing. The way I imagine it is step number 1 is capture the data in some form so they do not disappear. So in best practice contexts, above all else, make sure the data are not lost. Then secondarily, capture the information in such a way that the institution can get access to it. And then third, present that data -- you know, there is a way you can language this tiered way of making the data more and more accessible.

JEFF BOZANIC: What I am suggesting is should that thought be put at this point in the straw man document.

RICHARD PYLE: I can probably come up with a fleshed out version of this for tomorrow if you want, based on the conversations we have already had on it over the years.

NEAL POLLOCK: That is a good solution. Any other discussion on this right now? Next one. Information should be more readily available to buddy e.g., buddy HUD or loud critical alarms. Should you have those flashing lights so you can see the status of your team's rigs and have high profile alarms expressed in such a way that it is hard to miss for the partners. Electric shock, cattle prods. I see heads nodding. Anyone want to work on the language?

JEFF BOZANIC: I am looking at this thinking, yes, that would be nice to have, but is it reasonable to have given where we are with equipment right now today. In other words, is this going to be used as this is where we would like to see things headed? Or is this going to be used as a line drawn in the sand, you cannot use stuff unless the buddy HUD is deemed adequate.

NEAL POLLOCK: Remember, we are not proposing rules or regulations or guidelines. We are saying what should happen. There are units out there now that have displays.

JEFF BOZANIC: Something like this can be used in both directions, and we need to be very careful as to how they are phrased.

RICHARD PYLE: In the same way that your first couple of them were couched as research priorities, maybe these should be requests to manufacturer priorities. If we wanted to frame a class of these kind of points. If one class was: "Here are the research questions we would like someone out there to answer". Maybe we should also have a class of: "Here are the things we would like the manufacturers to consider going forward."

NEAL POLLOCK: That sounds good. What do you think?

JEFF BOZANIC: I like that. The former one with the black box data should have the same sort of thing in front of it, the prior point, should also have a request to manufacturers to improve data collection and stability.

RICHARD PYLE: What I was going to add is stuff we have already discussed. Here are the minimum pieces of information we wish all manufacturers would at least log and at what minimum granularity. And then optimally -- but the data one is even bigger than that. Even if the manufacturers give you everything you want, as Jeff was saying, you need something to aggregate that.

NEAL POLLOCK: We also do not get everything off the rig. There are some things like exercise intensity, thermal stress, that requires the diver to be involved to enter some data.

JEFF BOZANIC: And outcomes.

DAVE PENCE: In response to Jeff's question, I mean, my feeling is that this should be both a request, a statement of desirability to advise manufacturers, but also a statement of advisories to advise diving control boards when they are approving or disapproving specific equipment.

NEAL POLLOCK: That is a great point. It should not just be to manufacturers. Have we got a simple fix on this right now that will address that broadly?

JIM HAYWARD: Just as a note, recommendation to DCB.

LIZ KINTZING: You are not requesting this information from the DCB.

NEAL POLLOCK: No, this is not requesting information. It is saying this information should be available.

JIM HAYWARD: Recommendation to DCBs.

JEFF BOZANIC: Say DCB considerations.

NEAL POLLOCK: So you are saying request to manufacturers -- we do not want to make these too wordy. Can we come up with something that meets the goal with fewer words?

JIM HAYWARD: You could have request to manufacturers and list of statements there. And recommendation to DCB.

DAVE PENCE: These are topics that I have been rolling around in my head for a long time, not so much whether this or that. But there are a series of life critical states that we need to avoid. And it is not so much about the control systems or the monitoring systems. In many cases it is the human machine interface that actually alerts the diver or alerts the dive team to the existence of that state. And it is not so much whether it has to be standardized so it is exactly the same in every one, but it should be done in such a way that the alarm is separate from the monitoring instrumentation so it cannot be confused. I sent a couple of statements a long time ago that I think had the wording that I liked. It was long and wordy, of course, but I will try to find it to see if I can come up with a straw man for tomorrow.

NEAL POLLOCK: Okay. Right now we will call it Dave Pence plus.

DAVE PENCE: It is a human factors issue rather than a system control issue. It is the diver-machine interface. And the diver override, can the diver ignore. Is the dive team adequately informed of an existing problem rather than simply whether the control systems work?

NEAL POLLOCK: To me that is where the buddy HUD would make some sense.

DAVE PENCE: The buddy HUD would be one example of a system that would work. What I am specifically trying to do is not say that every system has to have the exact same.

NEAL POLLOCK: Good point.

DAVE PENCE: Every car has a master light that is off and comes on when your alternator goes bad.

NEAL POLLOCK: Now, we can certainly get rid of "standardized" to begin with and say, critical alarms should be communicated.

DAVE PENCE: Yes, separately from monitoring systems.

KARL HUGGINS: I want to add "unambiguously communicated."

MAURITIUS BELL: As we go through these, I know Dave and I have had discussions on this before in our diving control board. So when we look at this stuff, the discussion I have about open-circuit diving and so on. I also think we need to discuss when we look at incidents and accidents, what was the failure of the equipment or the failure of the diver to recognize a problem with the equipment, could that have been avoided or could that have been mediated by additional information. And a perfect example there is we have had this discussion a lot where we talk about additional failure modalities and so on for the diver, but I look at one of the greatest fatalities in diving in general is running out of gas. But there has never been a consensus statement or never been a recommendation for open-circuit divers to have air integrated computers that would beep at them when their gas gets low. But we could argue that some type of sensory to open-circuit divers to let them know when they are exhausting their gas supply, would make them aware of it. They would terminate the dive, share that gas, and not die. But we do not do it. And most of the community does not do it, recreational, scientific regardless. Rick and I have had discussion about what constitutes a competent rebreather instructor. Now we require 200 hours of instruction. A lot of other agencies require 100 hours. Rick made a really good point. What data suggests that the additional

100 hours makes a more competent instructor. I do not know. The more hours the better, but is it really necessary. So, similar to what Phil Short said regarding the number of hours that we are requiring. He feels the number of hours we are requiring for divers is very much on the light side, 50 h of instruction moving into mixed gas diving. What I am getting at is as we look at all these things, we also need to have a discussion about the efficacy of increasing numbers, increasing devices and so on as to how effective they really are.

NEAL POLLOCK: Certainly.

MAURITIUS BELL: I think it is great to have more alarms. Then you talk to a company like Shearwater. Shearwater does not put beeps in any of their equipment. They do not believe in it for a number of reasons. One of the reasons they said is they are a Canadian company. They all dive in neoprene and they cannot hear it. I think all of these need to factor in as we go forward and make a recommendation to the greater community regarding equipment.

JEFF BOZANIC: We have got the other document, the 50 items on straw man things. If we can go back to that and add how many hours should a research diver have before they get approved for 100 meter or trimix use or some means.

NEAL POLLOCK: We have that under progression.

JEFF BOZANIC: Never mind then.

STEVE SELLERS: While we are here, Neal, on this one, do we want the statement regarding workload while on rebreather? That is not task load. That is workload.

JEFF BOZANIC: Rebreather divers should avoid working hard underwater.

NEAL POLLOCK: On this one, now, I am seeing this as parenthetical when you have those examples, HUD or audible systems. It does not necessarily mean it has to be either.

DAVE PENCE: I just actually found my wording.

JEFF BOZANIC: Before you go on to that. I am just going to expand on your HUD alarm thing. Liquivision now has the ability to track setpoints from the surface and notify dive partners that their dive buddy is someplace else. Would that fall under the same kind of category as an appropriate technology?

NEAL POLLOCK: Sure. That is communicating with a buddy.

JEFF BOZANIC: What I am saying is that you have got HUD alarms or other technological or other communication methodology.

DAVE PENCE: So all of these are with regards to alarms or alerts for life critical failure.

NEAL POLLOCK: Let us do this tonight so we are not all sitting here too long. Does anybody else want to make any comments on this one just to get them out on the table?

SIMON TALBOT: It is probably more of a general question to people here, but one potential problem I can see out of providing information to dive control boards is that some dive control boards have no knowledge whatsoever of rebreathers. And the more stuff you say they need to know, the more scared they can get about people.

NEAL POLLOCK: On the one hand, you cannot use the justification that we would prefer to keep the diving control board ignorant because they would bug us less. That is not a very good best practice statement.

SIMON TALBOT: My desire is to find out whether or not you all have diving control boards that fully understand rebreathers. I have got one other person on my dive control board that knows about rebreathers and several who do not. Fortunately for me, they do not really interfere with what I do.

NEAL POLLOCK: If your diving control board is selecting the equipment --

SIMON TALBOT: They just say whatever you want. I do not see it as a problem for me. But I can see it potentially as a problem for other people.

NEAL POLLOCK: Leave that with us for wordsmithing, Simon, and we will see what we can do. Bailout options that do not require removal of the mouthpiece are recommended.

JEFF BOZANIC: I do not like it, quite frankly.

JEFF GODFREY: I do not really either.

NEAL POLLOCK: Not liking it and not appropriate are two different things.

JEFF BOZANIC: If you approve that, then you need to go on to say is there sufficient bailout gas available to whatever the bailout is plumbed to be efficacious. If you are plumbing it to an offboard dil bottle or an offboard bailout bottle, then you are connected to that system. You cannot change it between partners. When you are trying to remove or change gear, it becomes exceedingly awkward in many environmental circumstances. If you are diving it with a hypoxic mix, which is the next thing you are looking at there, it provides significant safety hazards when you are shallower or on the surface. I can think of lots of times when a bailout valve is not necessarily the best item to have in a system.

DAVE PENCE: Between "require" and "removal" insert "immediate." The whole intent here is that the system would at least provide immediate sanity breaths without the diver having to struggle to close a mouthpiece, remove it and pick up an open-circuit regulator. That does not solve all of Jeff's concerns and I recognize that.

NEAL POLLOCK: One of the things we have to remember is that we tend to have a few people who are outspoken. We have to make sure that everybody has the opportunity to weigh in.

RICHARD PYLE: I agree with most of what Jeff said, except I am not sure all of it is relevant to this point. I think everyone agrees there needs to be more bailout than just what the BOV can provide at the flip of a switch. I think the real question that we should focus on at this point is to what extent can mouthpieces with an integrated bailout open-circuit option be a liability? And the examples that have been given if you are plumbed into a hypoxic mix and you are trained to automatically go for that, yes, exactly. The thing is, Jeff, a lot of what you said is independent of whether or not your rebreather has a BOV. It is not that the BOV is a liability. It is that the BOV alone does not constitute a complete bailout strategy. So I think those should be teased apart as two separate issues to address. One, along the lines of what Dave was saying, does this group recommend that it is advantageous -- which is why the word "recommend" there -- to have the ability to quickly without removing anything from a diver's mouth switch from a closed-circuit source to an open-circuit source is one question separate from the bailout strategy issue.

DAVE CONLIN: For the isolation issue we have a lot of hypothetical issues, but we actually have two verified fatalities that would have been prevented by having a BOV isolator.

DOUG KESLING: Maybe you should place it in kind of a prioritized thing. One, there should be a bailout option. Two, first step would be bailout, open-circuit. Better yet, bailout with a bailout valve. If you are going to use a bailout valve, then isolate -- do it kind of in a, so that things are acceptable, but it is pushing to a more substantial or something that people want to drive towards.

NEAL POLLOCK: We can change this any way we want. The idea was bite-sized pieces, just looking at the valve and then making the isolation. Then we can go on to do other things. I think what we want to do is simplify rather than make it too complicated.

LES BURKE: I think there are two words on that page that are controlling. First of all, this is a guideline. Second word is "recommended." It does not say "shall." Okay. So everyone should have the ability to go before their DCB and argue as to why they are not using it in any given situation. It is a guideline and it is a recommendation. It does not say this is what you shall do.

RICHARD PYLE: Is the scope of this best practices document to make statements alone or is it within the scope to have sort of a, "Here are the advantages of having an integrated BOV and here are the disadvantages", and then sort of just make that as a statement. We all agree these are advantages. We all agree these are disadvantages. We are not making an assessment about whether or not it should be included as a mandatory feature.

NEAL POLLOCK: I think if we have points where we can legitimately make explanatory sentences that would be perfectly valid.

RICHARD PYLE: Maybe the solution to this particular best practices point is not we should have one or whatever. We all agree these are advantages. We all agree these are disadvantages. Whether or not we can emerge from that a more general consensus statement is something else.

RICHARD PYLE: We can solve it by saying instead of "are recommended," "have advantages in some circumstances but also have disadvantages in other circumstances." That does not help the reader in any way without enumerating them, but it is acknowledging that this group recognizes.

MAURITIUS BELL: I am on the fence with this one. I use the bailout valve, but I also train without one. I feel this is a training discussion. The reality is not using a bailout valve is a much simpler solution, across the board. I am not going to call it the best solution, but from a diver perspective, it is the simplest, uniform, option that works all the time regardless of the situation. When we introduce a bailout valve, we introduce complications. I am not saying those complications are bad. That is the reality. Putting in a blanket statement that says "we recommend bailout valves," is what I have a problem with.

NEAL POLLOCK: You are making a blanket statement saying that it is always better to not have one.

MAURITIUS BELL: It is advantageous to be able to switch to a known open-circuit gas, absolutely. But whenever we move from air diluent to mixed gas diluents and we start doing the type of diving that we have been heavily discussing over the last couple days, there is an added complication because you are bailing out to an onboard gas and at some point you are going to have to switch to an offboard gas. Versus the diver always being taught in an emergency off the loop regulator from the side goes in the mouth. Which at some point they might have to do anyway. In that sense, it is one practice that fits that works all the time. There is a simplification in that. I personally have a BOV. If we are going to make a recommendation, we truly need to think it through.

DAVE PENCE: As a trainer for a decade or more, I can attest to multiple situations of flooded loops simply because a flustered diver was so engrossed in a complex activity of trying to close a loop, get off the loop, and pick up an offboard regulator, that they flooded because in their rush they did not close the loop. Yes, in a rush, that is a training issue. It is a much more complicated series of muscle memory. At the same time, I also absolutely agree with the points that Jeff and Phil have raised about the risks of having a unit that has an integrated bailout valve and having plumbed in hypoxic diluents. That is a risk that needs to be managed. But there are ways to manage that risk as well by having alternate gas switching for the bailout valve. So there are additional measures that can be implemented so the bailout valve can still be a standard, simple action under stress and the diver is still not risking switching onto a hypoxic mix at the wrong time.

ROB ROBBINS: Our big issue is the bailout valve itself becoming inoperable. So we definitely want a secondary bailout system rather than use a bailout valve itself.

NEAL POLLOCK: Any recommendation can be rejected with sound justification.

PHIL LOBEL: I just wonder if some of these should not also be broken out by the rebreather and the operating depths. Whether you are using an oxygen rebreather in shallow water, whether you are someone like myself, no deco, 60 min shallow water, doing simple stuff and what is recommended. I have heard several times people referring to the extreme diving. There will be different recommendations for extreme depth diving and the complex gas mixtures you are dealing with versus someone dealing with a simple, shallow water rig.

CHRISTIAN MCDONALD: I want to echo that point. We talk a lot about the exceptional profiles that this technology allows us to access. That is not our community by-in-large. Deep diving is not going to be the bread and butter of the scientific diving community. But implementation of these pieces of equipment in the 20-50 m (66-165 ft) range may be. All of the hypoxic mix questions are critically important, but to a small subset of the community.

PHIL SHORT: My understanding from being here as a non-scientist is the hypoxic range community is tiny. The other point is one of the things that is not been mentioned, one of the single biggest advantages to a BOV within the depth frames is the buddy can swim up and simply turn it so the diver is breathing gas in an emergency.

NEAL POLLOCK: Very good.

STEVE SELLERS: Along the same lines, is there a depth range where not having offboard bailout is appropriate?

RICHARD PYLE: Is offboard bailout always required?

DAVE PENCE: I suggest that we do an evaluation of the current AAUS standards with all of its statements as specific straw men. Because I know for a fact that there is a statement in there that says simply the diver must have access to appropriate open-circuit bailout to terminate the dive. And it is that generic. So that if you are doing a very shallow dive that you can finish on your air diluent, it is all covered. So we have already got a whole series of straw men right there in the standard.

RICHARD PYLE: I wanted to come back to the point I made earlier. We are talking about two different things here. We are talking about bailout from dives and we are talking about when you flip the switch on the mouthpiece, does it simply prevent water ingress or does it also simultaneously give you open-circuit access. Those are actually fundamentally two different things. I have always hated the term "BOV" because it is more than a bailout valve. People equate bailout with "I am ending my dive. I am heading to the surface so I have access to these open-circuit gases." It is a separate issue as to whether or not you can, without removing anything from your mouth or removing your full face mask if that is the case, switch from closed-circuit mode to open-circuit mode. There are other reasons other than bailout you want to be able to do that. I guess I just want to come back to this point that maybe we should tease those apart as separate debates and the arguments that will not be conflated. There is the issue of what is your architecture for bailout. And then the issue is when you flip the switch on the mouthpiece, do we recommend that there is an open-circuit source there without removing or is that not on the list at all. To me, that is kind of what we are coming down to. I did not explain that well, but I hope you understand what I am trying to say.

NEAL POLLOCK: I get the idea. I am trying to figure out where we are going to go from here.

RICHARD PYLE: The way it is worded up there at the top. So already you have added the word bailout options. That might be framing this too narrowly as a separate question. This may not be a bailout option we are talking about. What we are talking about is the ability to switch from an open-circuit mode to a closed-circuit mode without removing a full face mask or a mouthpiece. It is one question which is separate from the issue of bailout options. I guess maybe that is where this is getting to be a confusing discussion.

DAVE PENCE: I agree with what Richard is saying. The diver should have the capability of immediately switching from open- to closed-circuit without the removal of the mouthpiece.

RICHARD PYLE: I am not even saying that.

LIZ KINTZING: Why do you not just say "bailout to open-circuit that does not require the immediate removal." That makes it clear that you are going to open-circuit.

RICHARD PYLE: I would get rid of the word "bailout." I think the example Phil Short brought up about the whole managing an unconscious diver. That is an example where you really would not call it bailout. You call it a rescue. To me they are two separate issues. And I think part of the reason we are having such a hard time with it is because we are conflating those two issues. Maybe you could tease those two issues apart and come back to the group with a fresher dichotomy, let us argue this question now and then argue the other question separately. It seems to me we could be more efficiently debating if we narrow the scope of the debate.

NEAL POLLOCK: Let us see if we can improve on this. We are pretty close to the bottom of the list. Let us see where we are at on these others. Rebreather modification should be discussed with and approved by manufacturers.

DAVE PENCE: Modification so that rebreather modifications affecting work of breathing. Whether it is just harness changes or things that do not affect work of breathing or functionality.

RICHARD PYLE: If it comes with a metal buckle on the waist strap and I prefer a plastic buckle. Does that count?

NEAL POLLOCK: Good point. Where do you draw the line? As was pointed out today, if a mouthpiece change can affect work of breathing.

DAVE PENCE: Modifications affecting life-support function.

RICHARD PYLE: Can I take the crotch strap off at least?

DAVE PENCE: Affecting life support functions. That is very broad, but it is work of breathing.

GREG McFALL: How about just compromises the integrity of the loop.

MAURITIUS BELL: I think this comes back to what the manufacturer is going to say in their guide. I cannot remember exactly what AP says, but there is a statement regarding the modification of the unit. It is just going to say it cannot be done, of course. Is this something we should really talk to one or two of the manufacturers about instead of putting a guide that then people are going to look at and say, we can do this as long as it does not affect the loop. Then the manufacturer may say --

AUDIENCE MEMBER: When it comes down to it, when there is an accident, they are going to go right back to their documentation. No matter what we put in this document, unless they are writing it down someplace and we have authorization for it in our hand, if an incident occurs, they are going to default back to their blanket statement.

MAURITIUS BELL: The work of breathing is heavily predicated on a number of things, including the position of the counterlungs. If you adjust your harness or the securing a strap in a certain way and that position changes, then that modification could be contributory to an incident.

AUDIENCE MEMBER: Including the crotch strap.

RICHARD PYLE: Actually, after I said that, I realize there are reasons, counterlung position being one, for which you do need a crotch strap.

SIMON TALBOT: Phil, you mentioned earlier, putting a canister inside the area between the counterlungs. AP do not like other pieces added to their units for exactly that reason.

RICHARD PYLE: I think the original wording is probably appropriate.

NEAL POLLOCK: Can we go back to this.

MAURITIUS BELL: I do not know. Yes, we can, but the reality is everyone in here probably has made some modifications to their unit, which is already between the institution, the diver, the DSO, the DCB and the manufacturer. Now, we as a body say they are in violation. Do we really even want to go down this road between the diver and the manufacturer or the user and the manufacturer or the DCB and the manufacturer?

NEAL POLLOCK: When you are a science diver, you have a responsibility to an institution. This is not just between a diver and manufacturer.

RICHARD PYLE: There are two safety nets in that statement. One is the word "should" as opposed to "must." The other is "discussed with and approved by manufacturers." In other words, if you are going to make a modification, I think an institutional control program ought to say at least find out if there is something you are not thinking about. So I think it is fair to at least go as far as to require discussion. You might quibble with "approved by," by I think "should" at least gets you covered on the "approved by." It is not going to constrain you too much.

NEAL POLLOCK: I think it is valid to remind people to be mindful of whatever is going to be done. And that is really what we are talking about in a best practice guidance.

STEVE SELLERS: If you just take out the "and approved by," then that let us them take back whatever information they have got and make their decision as to what they want to do.

NEAL POLLOCK: The inclusion of "approved by" was intentional. It precludes doing anything you want with the defense of "Hey, I discussed it with them."

STEVE SELLERS: Right. From an institutional standpoint, if I am told that and take it back to my board after they have asked me to check, my board is not going to let me make the modification.

NEAL POLLOCK: Okay, should we remove "and approved by." Phil Short indicates no. Dave Pence indicates no. We are getting four head shakes. Time for a poll. How many people think "and approved by" should stay in this guidance? Right now we are seeing the majority of hands for the affirmative.

KARL HUGGINS: The only thing is it is basically saying is the approval is by the manufacturer the way it is written there. Should be discussed with the manufacturer prior to approval.

DAVE PENCE: By the manufacturer. Any given one rebreather unit has one manufacturer.

ED O'BRIEN: I think you are looking too far into it. If you have the units, you should be in constant contact with the manufacturer to give them feedback. That is what the relationship should be. And they can advise you better on something that you might not have even thought of to accomplish your mission. I would not overthink it.

JOHN BRIGHT: Dialogue with the manufacturers, even within the scope of what they consider safe, off the rack, equipment configurations can help you. The example in my head is the back-mounted counterlungs that AP provides. Their harness or their air cell system has sewn in trim pockets for weights. It is no modification to use their air cell and put trim pockets on the top of the air cell. But now with the back-mounted counterlungs, the addition of weights in those positions puts pressure on the counterlungs when you are in the horizontal position and the recommendation is not to use them. Discussion with the manufacturer can prevent unintended consequences, even with approved products.

NEAL POLLOCK: Very good.

KARL HUGGINS: The discussion with the manufacturers prior to approval or prior to implementation.

NEAL POLLOCK: It is not just implementation.

KARL HUGGINS: Prior to institutional approval.

NEAL POLLOCK: We could change this to "and approved by the board." That does constrain the authority of the manufacturer.

DAVE CONLIN: I am going to agree with Karl. I think the likelihood that a manufacturer is going to approve anything other than what they are giving you is going to be pretty slim. So as a dive control board we look to the expertise to say this is as good as that. And I do not think that our manufacturers, particularly in the US, or, more appropriately, the manufacturers' lawyers, are going to let them allow anything other than what they provide. I think it should be discussed with the manufacturer but approved by the board.

MAURITIUS BELL: Almost everything is fine. I understand we are doing best practices. It is where I was going into on some of the other things on the big list that are all per the manufacturer's recommendations. I wonder if we really need to specify all these things that are intuitive. For any piece of equipment you use, it is always per the manufacturer's recommendations. It is fine if we are going to put it in. It is what should already be known to all OMs. Every piece of equipment you buy is always used and maintained per the manufacturer's recommendations. I am just wondering if it is moot.

NEAL POLLOCK: Steve made a comment here that this is not true for all equipment. It certainly does not hurt us if this is a legitimate statement.

MAURITIUS BELL: We should say approved by the manufacturer. That is what legal counsel will say. There is not really any way around that. You should always use in accordance with the manufacturer's recommendations.

DOUG KESLING: How about "rebreather modification should be in accordance with the manufacturer's guidelines."

NEAL POLLOCK: I do like the component of maintaining that dialogue with the manufacturer. That is one of the biggest strengths in the rebreather community that has waned in the open-circuit community.

RICHARD PYLE: What if "…rebreather modifications that deviate from manufacturer recommendations, should be..."

GREG McFALL: Or "which are not covered." I know for some of the components of the Megalodon are not covered in their manual. For example, BOVs require additional training and it is not covered in their basic manufacturer's guidelines.

JEFF BOZANIC: You can shorten that by saying "that deviate or are not covered by manufacturer's specifications."

PHIL SHORT: As per the discussion so far, the biggest, the most widely used platform in the room is the Inspiration, the AP system, which is under CE. Whether you agree with CE or not, this is America, not Europe. It is irrelevant. The manufacturer cannot allow changes to the unit. They will not let it happen, period. So the biggest platform used here and several of the other platforms used here, they would be legally negligent to allow you to make a change. There is just no justification for it.

LIZ KINTZING: I was told a couple weeks ago by Ed that if I was going to replace high pressure hoses I did not have to use theirs.

PHIL SHORT: But you will have to check with the manufacturer. Changing a hose is not necessarily a modification. Putting an after-market BOV, or back-mounted counterlungs when they are designed to be over the shoulder would be.

NEAL POLLOCK: We have made good progress. Those of you who have tasks can work on the text and we will get started first thing tomorrow morning.

(END OF DAY 3)

(DAY 4)

NEAL POLLOCK: We generated a number of discussion points yesterday. A small group worked last night to try and consolidate them and make them into operational statements. We also saw the need to defer some that likely could not be adequately addressed in the time we have available. We started with well over 50 points. We put 20 into the deferred category, but some of those were actually addressed through other points. What we present now are 34 points to deal with today if possible. The draft document will be sent to all the people who participated in this meeting with an open comment period.

The critical point is that what we do today is not binding and absolute. Wordsmithing issues will have to be addressed offline unless they are really significant. We will start with a quick pass over them to close the easy ones. Any needing discussion will be flagged and we will carry on. The goal is to reduce the active list and then address those one by one. Structurally, each point is shown twice on a slide unless it was too long. The top one was the original straw man, the lower one the revised form. Evaluating the bottom one is probably the best way to start.

We start with a preamble in which we placed statements concerning institutional authorization and periodic review. We then roughly grouped elements, starting with research priorities. The first might start us off easily.

Research priority: "Evaluating the efficacy of disinfection products and protocols." Any issues? No. Good.

LIZ KINTZING: Are we having anyone actually do this research?

NEAL POLLOCK: Great question, Liz. The idea of the research priority is to put our wish list out to the community. We would like to see the work happen, and perhaps the list will encourage investigators and help justify funding requests. We are saying we believe these items to be important enough to pursue. There are some mechanisms through which we can encourage the funding of this work. AAUS Foundation, for example, might provide a pathway. There is also a new external grant program coming online that will focus on rebreather safety research. Ultimately, though, we are promoting interest in these questions, not saying that this panel will be doing the work.

Research priority: "Collect, review and publish data evaluating oxygen handling in field operations." No issues.

Research priority: "Collect, review and publish data evaluating full face mask use and retaining devices, mouthpiece retaining devices." This actually came right out of RF3.

SIMON MITCHELL: Since RF3, the French have published a paper from their military in 2011 in Military Medicine. It described a series of 54 unconsciousness events underwater involving divers wearing mouthpiece retaining devices. They had three fatalities. I would suggest to you that three fatalities out of 54 events is way less than what you would have expected for unconsciousness events underwater. I do not know how we are going to get better data than that. I think it makes a strong case for the use of mouthpiece retaining devices.

> *Gempp E, Louge P, Blatteau JE, Hugon M. Descriptive epidemiology of 153 diving injuries with rebreathers among French military divers from 1979 to 2009. Mil Med. 2011; 176(4): 446-50.*

NEAL POLLOCK: This one could be addressed by existing literature.

Research priority: "Continue efforts to develop and implement reliable CO_2 monitoring technologies." Anybody want to bring this back for discussion? No. Remember, we can always come back to these.

Research priority: "Bailout strategies are complex and specific to individual circumstances and available equipment. It is recommended that a workshop be conducted to collect, review and publish information evaluating practice and safety." This one is a call for a workshop, possibly through AAUS in conjunction with the annual meeting. We are not saying we would put it on, but we certainly know people who could support the process. No issues?

JEFF BOZANIC: You are starting off on the easy ones.

NEAL POLLOCK: That was the plan. Now, the next point:
"Manufacturer Guidance - Life-Critical Alarms
Alarm(s) for life-critical failure states should be designed to be:
Unambiguously differentiated from standard instrumentation monitoring displays to reduce the possibility of being overlooked or ignored by the diver;
Expressed to the diver via at least two different sensory modalities (visual, auditory, or tactile);
Observable by other members of the dive team without action on the part of the diver.
* Consideration of human factors engineering of alarm systems from complementary disciplines such as automotive, aviation and aerospace safety engineering may prove fruitful for future improvement and/or standardization of critical alarm systems."

The asterisk represents a footnote to the main point. Anyone want to put this on the active discussion list? No.

JEFF BOZANIC: I think Dave with all the wording did a good job.

NEAL POLLOCK: Next:
"Deviations or incidents, even minor, should be documented and where appropriate the information should be shared with the broader community."
A bit of a mom and apple pie statement. There was some discussion last night as to how we approach this. You could be reporting internally. If it rises to the level that it is worth commentary to AAUS, or another reporting system, like one of the independent ones, including the DAN online reporting system. The idea is to keep track of events. When they look like they may be representing a pattern, make sure it gets advertised. No issues?

SIMON TALBOT: The only thing I would like to say, and it is probably covered anyway, is that the AAUS has some mechanism of reporting and broadcasting to other AAUS members.

RICHARD PYLE: The reporting mechanism might fall into the other point about data.

NEAL POLLOCK: There are actually two more that relate to data. So the main point here is to try to make sure that we have institutions capturing and preserving important data.

JEFF BOZANIC: The last statement does not make sense to me. Where possible, sharing that information, is that what you are supposed to be trying to get at?

NEAL POLLOCK: Yes. Let us leave this on the active list because it may be confounded when we are talking about the next, which is communication. The idea is, store the data, save the data, maintain it, and then when appropriate share it for research purposes. Then this is the idea of developing a system to aggregate. This was almost a research priority, but it seems this is ongoing. This will happen. But this is kind of the concept. We have the data. We make sure that we have got valid data. Then we have got a mechanism to feed it into with the appropriate ethical approvals.

DAVE CONLIN: There might be another step to include in there, which would be to interpret and present the data.

NEAL POLLOCK: Okay. We will hold this one for discussion.

Next: The call for AAUS rebreather standards update. The standards chair is nodding her head. Any issues with this one? No. Accepted.

Next one. "Rebreather modifications that deviate from or are not covered by manufacturer documentation should be discussed with the manufacturer and approved by the Diving Control Board."

UNIDENTIFIED SPEAKER: So if the manufacturer says, "do not do that," is that what you tell your board prior to doing it?

NEAL POLLOCK: You do not have a choice. That is the right interpretation. Let us leave this one open for discussion.

"Only absorbents approved by the manufacturer should be used."

DAVE PENCE: Keep it open for discussion.

NEAL POLLOCK: Very good. Next:
"Rebreather oxygen sensors should be recalibrated in accordance with manufacturer recommendations or at a minimum every time the absorbent is changed."

RICHARD PYLE: This one needs discussion.

NEAL POLLOCK: Very good. Next:
"Calculation of respired gas density should be part of dive planning. Ideally density should be less than 5.2 grams per liter and should not exceed 6.2 grams per liter under normal circumstances."
This comes out of the material that Simon presented and he drafted this text.

JEFF BOZANIC: Does this pertain to all dives? If we are diving air at a maximum depth of 40 m (130 ft), this does not really need to be done.

NEAL POLLOCK: No, but at the same time the computation is not all that onerous. You can do it once in that range and you are pretty much done. The question is whether there is any value in restricting it. Let us leave it open for discussion. That is all we are looking for here. If you have questions, bring them out. We are not trying to shut this process down. We are just trying to clear the ones we can.

Next:
"Elevated workloads can produce numerous risks to diver safety, including CO_2 retention, decompression stress or elevated decompression stress and susceptibility to oxygen toxicity. Diver workloads should be kept as low as practicable."

UNIDENTIFIED SPEAKER: You mean physical workload, not the complexity of the acts?

RICHARD PYLE: Not task, but physical exertion.

UNIDENTIFIED SPEAKER: This might present repercussions for authorization from boards.

NEAL POLLOCK: We will leave it open. Next:
"A switch from helium to nitrogen-based diluent during decompression is associated with a small increase in the risk of inner ear DCS. While this does not absolutely contraindicate diluent switches, in the majority of circumstances decompression safety may be best served by remaining on a single diluent."
Simon Mitchell provided this wording.

ROGER MAYS: You showed it on your curve yesterday. You can pinpoint those places where you think that happens. Is there a way to calculate that pre-dive?

SIMON MITCHELL: Not easily.

JEFF BOZANIC: That was based on a single dive. It does not pertain generally to all dives.

NEAL POLLOCK: We will leave it open. Next:
"Unit specific checklists should be used to ensure completion of essential steps in the build, pre-dive and pre-splash phases."
If you do not like pre-splash, some call it pre-jump, whatever you want. Conceptually, you have three elements, the build phase, the pre-dive and the pre-just-before-you-get-wet.

JEFF BOZANIC: I would like to discuss this one more.

NEAL POLLOCK: Okay. Next:
"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."

RICHARD PYLE: I do not know if you should let everyone know, but that is verbatim out of the AAUS manual.

NEAL POLLOCK: It is. We did not see how to improve on it. Any issues? No. Next:
"Rebreather configuration should provide the diver and rescuers with the ability to change the diver's breathing supply source from the breathing loop to an alternate, known, safe breathing gas supply open-circuit or redundant rebreather system without the removal of the rebreather mouthpiece or full face mask."

And the next point:
"Advanced systems incorporating gas mixtures which might be unsafe to breathe at certain depths should incorporate additional measures to prevent such an occurrence."

JEFF BOZANIC: The "should" is pretty strong.

NEAL POLLOCK: We will leave it open. Next:
"Divers are responsible to ensure that they are in health and fitness appropriate for diving. The decision to dive is that of the diver. A diver may refuse to dive without fear of penalty whenever he or she feels it is unsafe to do so. The ultimate responsibility for safety rests with the individual diver. It is the diver's responsibility and duty to refuse to dive if, in his or her judgment, conditions are unsafe or unfavorable or they will be violating regulations or the precepts of his or her training."

This was almost verbatim from AAUS.

LIZ KINTZING: Why is this here? This is the foundation of all of our manuals.

NEAL POLLOCK: Sure, and this is the best practice set of statements. It may be worth reiterating. We will leave it open.

RICHARD PYLE: I think this comes back to what we talked about last night. We do not have one that says divers should not hold their breath while ascending. There are some things that are so fundamental that maybe we do not need to reiterate.

LIZ KINTZING: Can I just make one more comment? At the beginning of the rebreather section it says that all the other stuff ahead of this, the other sections, which would be this, you have to follow.

NEAL POLLOCK: We are not developing standards here. We are making statements, some of which will undoubtedly make people just nod their head and say, yes, of course.

RICHARD PYLE: One way to look at it is that this group felt it was an important enough point to deserve a statement.

DAVE KUSHNER: I think it is important because we are considering a type of diving where manufacturers require specific training for each unit. Other scuba diving it is different; you can use any type of regulator and do any type of diving. I think maybe the wording should change a little bit, but I think for the specifics of CCR it will be important.

NEAL POLLOCK: Thank you. We will come back to it. Next:
"The prebreathe duration should be sufficient to verify oxygen control system functions. The prebreathe procedure cannot reliably detect a missing or compromised scrubber. The prebreathe should be conducted as close to the start of the dive as practicable."
This is shifting away from a stock, five-minute prebreathe. Some units require longer time to activate temp sticks; some do not. It is really to test those oxygen control systems.

LIZ KINTZING: You just mentioned temp sticks. If you have got oxygen in there, should not it be if there is CO_2 stuff.

NEAL POLLOCK: We will leave it open. Next:
"It is recommended that manual negative and positive tests should each be maintained for a minimum of one minute."
It may need some wordsmithing but I think the concept is clear. Any issues?

JASON LEONARD: Should not this one and the previous one go with follow the manufacturers' recommendations and guidelines?

NEAL POLLOCK: We will come back to it. Next, mixed team training:
"Open-circuit team members must be able to read PO_2, add oxygen, add diluent, and operate the buoyancy compensator. Closed-circuit team members must have available breathable gas accessible to open-circuit divers."

Next:
Cross platform diving. "Team members must have operational familiarity with each unit and be able to effect both assist and rescue procedures."

DAVE PENCE: Perhaps we should keep this up for consideration of combining it with the previous one. They are essentially the same concept.

NEAL POLLOCK: We will leave it open. Next:
"Management of an unresponsive closed-circuit rebreather diver should be included in diver training. Accident response plan and forms should be developed referred to UHMS guidelines (Mitchell et al. 2012).

JEFF BOZANIC: Leave it for discussion.

NEAL POLLOCK: Next:
"Proficiency should be documented with a minimum of 12 rebreather dives and a minimum of 12 hours underwater time annually. Dives to count for proficiency will be no less than 30 minutes in duration."
To give you a little bit of back story here, we were trying to not enable the person who does the 10 min dive repeatedly to qualify. We also did not want to penalize those who might be on closed-circuit O_2 units and only doing 30-45 min dives. It looks like it is open for discussion.

Next:
"Depth progression and unsupervised operation require demonstrated diver competency."
We may have to debate this whether or not we need it. We will leave it open.

Next:
"Pre-operation workup dives are recommended to establish diver competency."
Should this be kept open? Is it good enough to say it is something we want?

LIZ KINTZING: I think that needs to go with proficiency somehow.

NEAL POLLOCK: We will leave it open for discussion. Now to what is on the deferred list:

- Scheduling and number of dives to maintain currency
- Initial training requirements / Cross-over training requirements
- Entry level skill requirements
- Training requirements for non-divers (straight to CCR)
- Skill and rescue schedule and requirements
- Task loading progression, environment progression schedule
- Topside support recommendations/considerations
- Guardian Angel requirements
- Multi-institutional operations
- Days off, operational limits, fatigue
- Which units are approved for program use (3rd party testing requirements)
- Vetting of 3rd party equipment reviewers / Unit testing requirements
- Policy on modifications outside manufacturer norms
- Approval of algorithms
- Real time diver tracking

DOUG KESLING: About the practicality of the cell checker and whether or not --

NEAL POLLOCK: Let us, if we can, add it at the end.

DOUG KESLING: That is fine. I just wanted to throw it out there.

RICHARD PYLE: Do you want to make the point that anyone can champion one of these.

NEAL POLLOCK: Yes. Thank you. If anybody wants to champion any of these points, we will bring it back into the main body. These were items that we thought were either beyond the scope of what we could manage today or they were covered in some of the other statements on the list. The deferred list will appear in the document as an aide memoire.

LIZ KINTZING: Do we have scrubber in the other ones?

NEAL POLLOCK: Yes. One on scrubber and following manufacturer guidelines. As I said, some of these were addressed in other points.

SIMON TALBOT: The skill and rescue schedule, was that referring to rescue skills or much more broadly?

NEAL POLLOCK: That is a question for this group. We did talk about rescue in one that was developed. So the open question will be whether it adequately addresses what the group wants.

DAVE PENCE: Whatever we decide to leave on this list, in your final guidelines I think a brief discussion and identification of these topics as future points for discussion is imperative.

NEAL POLLOCK: I will tell you how it was envisioned. The draft that we send around would not be that much different from how it appears now, but in the final proceedings, there would be a list of items that is described as deferred for broad reasons such as being beyond the scope of this meeting. It would probably be a sanitized list. We are not trying to hide anything, just keep things clear, if possible.

JEFF BOZANIC: That very first item I think we would be remiss not to address is the people that are not CCR supervisors at different institutions. I think that is important enough that you ought to put it on the other list.

NEAL POLLOCK: Okay. Let us get a couple of other comments here.

GREG McFALL: The ones that we had related to scrubber were the manufacturers' recommendations calibrating your O_2 sensors with your scrubber change. But when to change your scrubber is something that I would like to have some dialogue on. Because people have this mentality that they have got this bank in their stack and if you have got a four-hour stack, you can dive it two hours today, put it in your garage for a month, and come back and you have still got two hours on your scrubber. So those are the kind of aspects that I want to talk about.

NEAL POLLOCK: We will reclaim any needed during the break as new bullet items. Yours will be added at the same time, Doug. Does anyone else want to champion items on this list that they think should be pulled back onto the main list?

JIM HAYWARD: How about the multi-institutional operation, I do not know when you are going to get a better audience to discuss it than we have today.

NEAL POLLOCK: Okay. Any others?

UNIDENTIFIED SPEAKER: I think it will definitely be something that has to be taken at a different time, but a change in the wording as to which units are approved for program use, maybe recommendations for approved units, like criteria that you can use to select.

RICHARD PYLE: Even if we do not come back to it, we should think about rewording it.

NEAL POLLOCK: Very good. We will pay attention. Okay, let us see if we can march through the list for discussion. It will not be perfect, but I will remind you again that we have the ability to review the draft in an open comment period. So let us not waste time on things that can best be handled offline.

We are back to the research priority. "Collect, review and publish data evaluating the efficacy and validity of the oxygen limits including CNS, pulmonary, hyperoxic, myopia" --

RICHARD PYLE: Go up. You missed one.

NEAL POLLOCK: That was okay. We already decided on that. Now we are on to the next one.

Research priority: "Collect, review and publish data evaluating full face mask and mouthpiece retaining devices." Simon made the very good point that there is some literature out there. The question is whether the point requires more original research or just bringing it back to the community.

RICHARD PYLE: I still think this point is valid as a separate point. Because we can take that publication as sort of the elephant in the room of that summary. But we could also canvas the opinions and practice of the diving community and supplement it. So, in other words, I think we can do just pointing to that publication. I think it is worth including it.

NEAL POLLOCK: Does that make sense to you, Simon, the idea that there may be enough data out there, but it may not be in the hands of all the people right now so it would be worth pulling it forward?

SIMON MITCHELL: I have no problem with that. I actually think there is enough evidence out there to move forward with some hard recommendations, but I do not think that is something that can be done here this morning. What it really required is some people like you and I to sit down and write a paper on it and get it published.

NEAL POLLOCK: That is why it is a research priority.

SIMON MITCHELL: I think that is fine. It is just good news that we are actually closer to this goal than most people think.

DAN MONSON: Just for us, we have these Aqualung rebreathers, and they are made in France. They told us that it is highly recommended to use the mouthpiece retaining device, and they kind of said you are crazy not to.

NEAL POLLOCK: What are the other opinions on mouthpiece retaining straps? Thoughts? Experiences?

JIM HAYWARD: I am going to ask, what is the downside of using one?

UNIDENTIFIED SPEAKER: Uncomfortable.

JEFF BOZANIC: I am going to say I have no experience and I do not know how we would retrofit a lot of the existing mouthpieces that are on the market already to include some kind of retaining device. So that is something that we would need to look at as well. We could recommend it all we want, but if we cannot figure out how to put it on an Inspiration or a Meg or whatever it is you are using. We need some additional assistance in being able to implement this.

NEAL POLLOCK: Remember that we do not necessarily have to do all the work.

DAVE PENCE: I was just going to say to Jim, in my experience working with Mark Vs at one point, the biggest problem is it makes it very difficult to remove the mouthpiece when you want to, which, if you need to switch to open-circuit, makes a requirement that you have a way to do that.

SIMON MITCHELL: Dave, it does not make it difficult to remove them, not the properly designed ones. The ones that the French Navy used in their work are the Draeger mouthpiece retainers, which have been carefully designed. They come as essentially a complete product that is your mouthpiece and the retainer all in one. And to address Jeff's comment, they kind of bolt on. They go on as your normal mouthpiece does. They come with a flange and a strap. They are not hard to remove. You just yank it out. The strap is designed to be quite flexible. It is just right. You can probably break them if you were really in a big hurry. But I disagree that it makes it hard.

JEFF GODFREY: We were talking about retrofitting. Best practice does not mean everything we bought is out. You do not have to go home and throw them out of your dive locker. It means that in the future when we are shopping for products, this is what we, the diving control board, consider.

BEN WEITZMAN: This has come up in our conversation, the oxygen rebreathers, is that we have used head strap retaining alternative devices or something else to increase the likelihood that a mouth piece will actually stay in your mouth.

NEAL POLLOCK: And did you have that mouthpiece change approved by the manufacturer?

RICHARD PYLE: That is my question. Does adding a mouthpiece strap require approval by the manufacturer? Is that a modification to the rebreather. That is why I wanted to parse what is a modification to a rebreather.

JEFF BOZANIC: This says "Research priority: Collect, review and publish data." This is not saying that we have to have it. I think this is a great priority the way it reads.

NEAL POLLOCK: The wording was purposely neutral. This could be another promotion of a special topics workshop. It could be that a one-day workshop address two topics. This could be one of them.

SIMON MITCHELL: Neal, I am sorry, but I want this on the record. Paul Haynes, a man known to many of us as a rebreather designer, ex-military diver, is actually generating a discussion paper on this very issue where he is doing what I suggested before. I do not want it to sound like I am plagiarizing his idea. He is doing it; I have been giving him a bit of a hand with that. Hopefully that will be something we will see in the near future.

NEAL POLLOCK: So it seems like this pitch is probably reasonable. We have got some data out there. We need to pull it together for this community. This seems like a reasonable statement. Let us put it to bed. Thank you all. I think discussion in these sessions are going to be really good. And I will remind you that we will be editing the transcript to clean up the text, but trying to retain the content. Next point:

"Institutions should capture, maintain and share as appropriate information about individual dives and divers, e.g., dive computer downloads, time-depth gas mix and PO_2, diver demographics, and diver status.

Where possible, in standardized format and where appropriate." And this should say "where appropriate available for de-identified sharing."

RICHARD PYLE: Something like that or that last point might not even be relevant given the next point. Maybe it folds into the next point.

NEAL POLLOCK: Well, the standardized format is not obviated by the next point.

RICHARD PYLE: Except that the reason for a standardized format is so you can aggregate different data sources. In other words, each data source will have its own format. So what you would really want to say is, "in a form that can be transformed into a standardized format for aggregation purposes." I thought we were actually combining the aggregation with the collection. This is feeling like a wordsmithing thing. I do not know if there are any issues.

NEAL POLLOCK: Any problems with this? What I am envisioning may happen is if people are happy with this and they end up being happy with the next one, in the review we may say, that is sounding redundant; let us drop it. Does anybody have a problem with anything they see here?

JOHN BRIGHT: Would not collecting data in a standardized format also require that the institution standardize how they rank and categorize the data, for example, unified categories of thermal stress.

NEAL POLLOCK: Yes.

JOHN BRIGHT: So there would be another level of not just figuring out what data we want but figuring out institutionally how do we record that in such a way that it is unified.

RICHARD PYLE: In my other world I work on data standards for biodiversity. And generally the solution over the last 20 years of doing that is not so much about telling people how to store the data on their own, but publishing an exchange standard. "Here is a standard for how we want to exchange information." And that guides people in their own systems. They can do it any way they want as long as they realize what they want to be able to transform it into. And I do not know if that is a model we want to follow here. That gives individual institutions the flexibility to store it any way they want, but being aware of what the standards are, they store it in such a way that it can be transformed into that standard. I do not know if that addresses your point.

DAVE PENCE: From a philosophical standpoint, I completely support this. As a program manager looking at the additional workload of having to document, to manage this additional information in-house, I have some logistical concerns. And I think that if this recommendation is going to be made, there needs to be a recognition that that workload has to be accommodated in some manner.

NEAL POLLOCK: Again, best practices guidelines. Our interest is taking off the hat of "this is adding to my workload" and saying "what is the right thing to do." And then presumably if somebody is operationalizing this, they would be saying to their administrators, look, this is taking more effort that needs to be supported. I am not sure that we need to put a statement like that in here, but we can.

JEFF GODFREY: I think we have got something in there that talks about better data management tools and priorities that might address that.

JEFF BOZANIC: So the only change I would make here is on that last line just add referring to the sharing, just to clean up the wordsmithing.

RICHARD PYLE: Shareable in standardized.

NEAL POLLOCK: Thank you. Anything else on this? I am not going to put it to bed just because there is a little bit of an open discussion. But I think we can possibly put it to bed once we address this next one:

"A system for aggregating data on diving activity within the scientific community, including data exchange standards and protocols and development of data management tools is highly recommended."
Dave, as part of that process, I would anticipate there you would have a statement where you are acknowledging this would probably be additional work for participants, but the benefit to the broader community would be improved.

RICHARD PYLE: And the development of data management tools could make it much less of a burden if done well.

NEAL POLLOCK: Are these two as a pair comfortable? Can we close out both of them? Anyone have any concerns? All right. We will close out both of these items.

DAVE PENCE: A system for efficiently aggregating data. Yes, I would like some recommendation in here. We can make recommendation for capturing every piece of information in the world and it is meaningless if it is not achievable in a reasonable fashion.

NEAL POLLOCK: And I would think under data management tools that is implied. Does anybody have a problem adding "efficiently" in there? Anything else on this one? Okay. We will close it. Next.

"Rebreather modifications that deviate from or are not covered by manufacturer documentation should be discussed with the manufacturer and approved by the Diving Control Board."
The question here was whether it was understood that if the answer was no questions would have to go to the diving control board.

MAURITIUS BELL: I do not agree. We should put in "has to be approved by the manufacturer." Right here what we are saying is that we are saying that an OM can discuss it with a manufacturer, get it approved by the DCB, but there is the possibility that the manufacturer does not approve it, but it could still be approved by the DCB. I do not think as a body that we should sanction such behavior.

CHRISTIAN McDONALD: Speaking from an institutional standpoint, it is well within our purview to do our due diligence, assess risk and make determinations that deviate from -- we are able to assume whatever liability and risk we are able to assume. So I do not have any reservation with this because certainly any modifications should be in consultation with the manufacturer. And if you are going to do something that they do not support, then you as an institution are welcome to assume that additional risk, but that conversation is critical. So, I mean, the DCBs are going to do what they want and institutions are going to do what they want.

MAURITIUS BELL: That is why I say we should not put it in there.

CHRISTIAN McDONALD: I would much rather that we codify that they need to be talking with the manufacturers.

DAVE PENCE: I am in complete agreement.

LIZ KINTZING: Same thing I was going to say.

MAURITIUS BELL: I feel that we ought to pass that by somebody with some legal expertise.

JEFF BOZANIC: This is a best practices guideline that is coming from this group. That is already been stated. I also favor this. Maybe this is one we just call for a vote and Mauritius obviously does not agree.

NEAL POLLOCK: For any of these that are contentious, we will call for a vote. This is a consensus group. But first let us get some more discussion.

GREG McFALL: I agree with Mauritius in principle, but, you know, as a best practice, I feel like the onus is upon us to put out what we feel like are best practices, even if they are obvious. Because this one, to me, is the idiot-proof statement. Because somebody might come up and say, I do not like my counterlungs over the shoulder. I am just going to take them and put them on my back. I think this one needs to be in there because I think we need to point out the things that make it obvious that this is a best practice. And they need to be reiterated.

PHIL LOBEL: I think the one thing that we are missing, and I agree with what Christian is saying, is that although this audience might not represent but we do have people at our universities who are very experimental who do develop new technologies. And someone might be a physicist who is putting together a unit that is modified. So a manufacturer might not approve it, but it might be funded for ONR or someone for future development. So we do not want to cut off our ability to do advanced research, but certainly the Diving Control Board is going to make sure that whoever is doing this is qualified technically to do what they are proposing.

MAURITIUS BELL: Just for clarification, I am just thinking from a legal perspective from AAUS. That is my only concern. This is what we should be doing, yes, but I am saying have we looked past this group and thought about any legal implications. I am not a lawyer.

RICHARD PYLE: I want to point out that United States federal regulations require that the Diving Control Board have complete and autonomous control over all diving. So ultimately, that last point there, which seems like the contentious point, is actually dictated by OSHA regulations. Ultimately, it is not the manufacturer. The Diving Control Board has complete and autonomous control.

LES BURKE: My question is simple. How many DCBs of the folks in this room do not have an attorney? The reason I ask that question is no institution -- no attorney is going to say, okay, let us go against what the manufacturer says. Risk management-wise, I just do not see anyone, any institution, saying, okay, we are going to do what we want to do in spite of that.

PHIL LOBEL: Unless it is in the experimental mode. Unless someone is an engineer designing something. We are confusing normal operational capability with someone at our institution that might be working to refine and advance the technology.

DAVE PENCE: I can tell you that there are modifications to rebreathers that we have proposed or asked the manufacturer about that are not included in their manual and they have specifically said, sure, that is okay. So this process is workable in some circumstances. They are not always going to say, no, you cannot do that. In fact, many of the modifications, such as back-mounted counterlungs, have come out of that consultation between end users and the manufacturers. So you cannot really say that the manufacturer is going to deny all modifications. But having that ability to consult with the manufacturer, especially with regard to unforeseen consequences of the modification is critical for a Diving Control Board to feel comfortable about allowing that.

RICHARD PYLE: One other way to look at that last point approved by the DCB is just because a manufacturer approves it does not mean the DCB will automatically rubber stamp that approval.

NEAL POLLOCK: This wording does allow you to go in all directions. Now, do we have any new comments? Let us see if we can reach a consensus on this. If not, we will defer it for later. How many believe this should stand, allowing a little bit of wordsmithing. We have a clear majority. Does anyone argue with that? No.

RICHARD PYLE: Do you want to get on record the reverse?

NEAL POLLOCK: Thank you. How many people believe this is inappropriate to include? I am not seeing any hands. No one is saying that they think it should be excluded so we accept this and move on.

DAVE CONLIN: Just point of process. Maybe this would go faster if we get to these things if we do this before we have discussion. And then we can see what people think about it one way or the other.

NEAL POLLOCK: We established these as the points needing discussion. And the discussion is of value for the record. Next:
"Only absorbents approved by the manufacturer should be used."

DAVE CONLIN: I can imagine a situation where a manufacturer would produce their own absorbents and say that only their absorbents are recommended.

RICHARD PYLE: Yes, Draeger did do that.

BRETT DODSON: It looks to me like this is definitely going to hand tie what we were discussing. You talk to the manufacturer. You say I prefer to do this. They say absolutely not. You go to our Diving Control Board, our risk management, our general counsel says, have at it. This kind of goes, manufacturer says no. Who is taking the liability?

DAVE PENCE: First off, we all assume liability in everything we do. All you can do is assume that risk and liability in an informed manner, and that is what the Diving Control Board is supposed to do. Secondly, the AP diving platform is a classic example of this. They have one absorbent that is certified for use to perform in a specific manner and provide the recommendations. But Martin Parker has repeatedly said in open forum, yes, I have used other sorbs appropriately. There are some that do not work, and by the way, these are the ones that have not worked well. Most of them are medical grade. But he has also said, you can do it. Just be aware that the performance is going to be reduced by approximately this much and your instrumentation may not be correct. So it is not that the manufacturer has said no. It has been an excellent consultation with the manufacturer about the implications of using a different source. So, again, to me, that is a perfect example of why we should be consulting with the manufacturers or the designers.

NEAL POLLOCK: Dave, with your position, do you believe this wording is appropriate?

DAVE PENCE: No. I think this should be included in the same wording as the one for modifications. Any modification should be made under consultation with the manufacturer.

SIMON TALBOT: I was going to say the same.

NEAL POLLOCK: We are coming close to a motion on the table. I want to hear a little more discussion.

PHIL SHORT: This should be linked to the independent testing on the extra list at the end because many manufacturers' platforms have been certified through independent testing to several different types of absorbent that are all approved so they are not trying to be exclusive to one.

NEAL POLLOCK: Would the manufacturers accept that, do you think, and would it end up on their approved list?

PHIL SHORT: If they have tested with that absorbent, absolutely. If they tested four different types of absorbent, they approved two.

DAVE KUSHNER: This should be added to the previous one and just say add "consumables."

NEAL POLLOCK: "Including consumables"?

JEFF BOZANIC: I concur with what Dave said, and I want to add one more thought. Operationally, you travel to someplace that is relatively remote. Not all of your supplies come, including your absorbent. There is absorbent that is available onsite that has been used or may be appropriate, Sodasorb is available and not sofnolime. Yet, sofnolime is the only thing that has been tested and approved by the manufacturer of your particular unit. You do not want to tie your hands quite too much. So Dave's comment about utilizing or consulting the manufacturer or leaving the ultimate decision to the DCB would seem to make more sense to me.

NEAL POLLOCK: Does adding "including consumables" to this point address the issue and we can remove the next point without losing anything?

DAVE KUSHNER: I would just put it after modifications. Modifications, parentheses, including consumables.

DAVE PENCE: I have one more comment. It is an observation that this same general principle of consultation with the manufacturer would probably also apply to any extension of use beyond the certification limits. For example, many of us do dive a rebreather deeper than 100 m (330 ft), which is the standard depth to which the unit is tested. That does not mean it will not work deeper, but certainly further consultation with the manufacturer as to the implication of that is a good idea.

PHIL LOBEL: Exceeding defined operational limits.

NEAL POLLOCK: Very good. Any more issues on this one? No. Next:
"Rebreather oxygen sensors should be recalibrated in accordance with manufacturer recommendations or at a minimum every time the absorbent is changed."

MAURITIUS BELL: I feel that one huge statement about discussion with the manufacturer and approval of the DCB could be employed. Whatever the operational parameters that the manufacturer sets forth for the use, I feel that all of that will fall under in accordance with the manufacturer.

NEAL POLLOCK: To give you some background, this one arose from a comment that a lot of manufacturers do not go into detail on some of these points. So there may be no documentation. This was intended to go further for cases where you have no documentation. Anybody want to correct me who was participating in that last night?

DAVE CONLIN: It does not satisfy me because every time the absorbent is changed trumps the manufacturers' recommendations. There are rebreather configurations out there that are designed that you calibrate the sensor at the beginning of a project, for example, and then you run it over the length of the project, not every time you change.

NEAL POLLOCK: And that is the point that is being made here. This is going beyond that you can do once and hold. That is the question under debate.

RICHARD PYLE: I was going to say if the manufacturer has no recommendations, then we fill in that void. But I guess the point is that there may be a way to word this so that it never contraindicates what the manufacturer says. And then that secondary provision is only legitimate in the context of no manufacturer recommendations.

JIM HAYWARD: Again, this being a best practice, if it is the best practice to go with this schedule, and it is more conservative than the manufacturers', then it is an appropriate statement, I would say.

DAVE CONLIN: I have a response to that. Operationally you could run into situations where you have to disassemble a functional rebreather with integrity to test the O_2 sensor, potentially introducing more chances for problems. So I would say that it is not always going to be the best practice.

PHIL LOBEL: I think this is going back to the best practices and why you should do that. O_2 sensors are not always that reliable and they do go out of whack for a variety of reasons. So in one sense it is almost a research priority on oxygen sensors. In our community that wants to be very safe and minimize risk there would have to be a compelling reason not to recalibrate every time.

LIZ KINTZING: I want to know why the scrubber is driving this recalibration? Why not a diluent change?

UNIDENTIFIED SPEAKER: Why not a cylinder change?

RICHARD PYLE: I had the same question. I do not know where this came from.

NEAL POLLOCK: I do not remember where it came from either. We will table this one for now and come back to it. Next:
"Calculation of respired gas density should be part of dive planning. Ideally density should be less than 5.2 grams per liter and should not exceed 6.2 grams per liter under normal circumstances."
To address Jeff Bozanic's earlier comments, it seems to me that if you compute for a particular gas like air and know when these gas densities are less than the cutoff you can just sign off with no further effort. You have met the dive planning and hopefully keep the issue in mind.

JEFF BOZANIC: That is fine. I just did not want this to show up on a form to be done every day by every diver.

NEAL POLLOCK: If you have documentation specifying that you are below that limit through a specific depth, that could suffice. I do not think it requires long hand math every time, but it stands as a reminder.

JOHN BRIGHT: This might be a syntax issue, but is the nature of the data driving these recommendations sufficient enough that we can use the word "ideally" as a recommendation?

NEAL POLLOCK: That is a very good question. Simon, you want to respond to that?

SIMON MITCHELL: Is the question that ideally is too strong or too weak?

JOHN BRIGHT: Is the nature of the data sufficient to support the use of that word?

SIMON MITCHELL: I would say so. I think it is the best data out there. It is virtually the only data out there. And it is pretty convincing.

DOUG KESLING: Just a suggestion. Is there a possibility we could formulate a table for a quick view?

NEAL POLLOCK: Sure. It would not be difficult to do. The key element is that it should be considered in the dive planning. Operationalizing it is pretty straightforward.

PHIL LOBEL: I think some of these sort of fall into the categories of diving at deeper depths versus what a lot of my part of the community does, which is diving at 60 ft (18 m). So some of these should have a caveat or some explanation that if you are doing dives at deeper depths or extreme dives, many of these hold. But if you are doing what I would consider a typical, average, scientific dive less, no decompression, you are using the rebreather for extended bottom time at 60 ft to do normal work, this is not really going to be important. We should be able to check off whether we are in that group.

NEAL POLLOCK: I think you could argue that the gas density concept is important enough to be worth embedding.

PHIL LOBEL: It might be, bringing it to the training.

SIMON MITCHELL: Phil, I think we are in danger of over interpreting this. It is not to say that people need to sit down with a calculator before every dive and check the gas density. I think it is going to become institutional knowledge very quickly where the boundaries are where you have to start thinking about it. I think this is a principle that is actually really important. And it has been one that has been overlooked by the diving industry in the broadest sense, recreational, professional, for a long time. I do not see the harm in this statement. It will take five seconds for people to realize that 5.2 grams is air at 30 m (100 ft); 6.2 grams is air at 40 m (130 ft). If you are inside that range, then it is going to be obvious you do not have to think about it. I think that is going to become very clear very quickly.

RICHARD PYLE: Would it alleviate it a little bit if this point was prefaced with "for dives conducted deeper than 30 m (100 ft) or with gas densities greater than air." That way people do not have to worry about it.

NEAL POLLOCK: That is adding to the complexity. It does not make it better.

RICHARD PYLE: I was just trying to make it lighter.

JEFF BOZANIC: Let us keep this the way it is, but let us in discussion on the workshop proceedings put, these qualifications are met by somebody doing a dive at X depth on air. It does not need to be done for any of those kinds of dives. It really is a consideration. If we qualify this with a paragraph or a couple sentences after this particular point, that meets the discussion point of, pretty much meets all of the reservations that all of us have and it gets the concept and the literature that Simon wants to have, which is we need to be thinking about this in other areas. Does that make sense?

MAURITIUS BELL: It is really no different from the MOD or any of the other calculations that we do.

LIZ KINTZING: I want to point out that it says "should," not "shall." It is not saying you have to do this.

NEAL POLLOCK: There is no real value in making it more complex. It is very simple to do almost instantaneously in a lot of the circumstances. Do we leave it open or do we close it? How many are in favor of accepting this as it is written? That looks nearly universal. Any opposition?

JEFF BOZANIC: I would just like to add a little bit of clarification to the statement in the proceedings or the workbook when you put it out.

DAVE CONLIN: No.

RICHARD PYLE: Again, no.

SIMON MITCHELL: Jeff, we had a fairly lengthy discussion of this in my paper.

DAVE PENCE: Just as an observation, I do not recall seeing a similar best practice guideline for END. Should we have one regarding nitrogen partial pressure for END.

LIZ KINTZING: There is, I think, 120 ft (37 m), somewhere in there.

DAVE PENCE: We are talking about this, which is very legitimate.

NEAL POLLOCK: The key difference is that the other is institutionalized. This one is not.

DAVE PENCE: I have no argument with this whatsoever. I am just making an observation that perhaps there are other similar types of statistics that we should identify and codify.

LIZ KINTZING: If you follow this, it will take care of your END. Simon, is that correct?

SIMON MITCHELL: My comment about END and this, it is really the other way around. You cannot assume by looking after your END, you will be looking after this. You need to do it independently. In many circumstances you will look after both by looking after one, but I do not think you can rely on it. If you play around with the numbers, you will see what I mean. While no one else is saying anything and Neal is typing, I will be presenting the original data that leads to these conclusions. It will be the first place this has appeared in the world. Gavin Anthony has not published this anywhere else. These proceedings will be the introduction of this to the world of diving. And I think that is really exciting. I think it is important. I think the data is solid, pretty convincing. And there will be commentary in that paper that will address Jeff's concerns.

NEAL POLLOCK: There were no other questions so assuming that still stands, we will accept it. Next: "Elevated workloads can produce numerous risks to diver safety including CO_2 retention, increased decompression stress and increased susceptibility to oxygen toxicity. Diver workloads should be kept as low as practicable."

DAVE CONLIN: I do not have any problem with this except for the last sentence. I would argue for "diver workload should be a part of dive planning. Anticipated diver workload should be a part of dive planning."

DAVE KUSHNER: I concur.

RICHARD PYLE: Is not that covered by "as practicable?"

DAN MONSON: I do not know if it matters, but do you want to clarify that it is physical workload again?

NEAL POLLOCK: Yes. Wordsmithing. Dave, you want to give us more alternate wording to consider?

DAVE CONLIN: Diver workload should be a part of pre-dive planning. Diver physical workload should be a part of pre-dive planning.

NEAL POLLOCK: Or exertion. Would this help if we said "exertion" rather than "workload?" Elevated physical exertion can produce numerous risks to diver safety, including CO_2 retention, increased decompression stress and increased susceptibility to oxygen toxicity." Diving exertion. Yes, diver exertion should be considered.

RICHARD PYLE: That is a wordsmith thing.

STEVE SELLERS: The question for me comes up should we be giving some sort of direction on what physical exertion is?

NEAL POLLOCK: We could bring back the last sentence now and say "optimally, exertion should be as low as practicable."

MAURITIUS BELL: And should be considered as part of dive planning.

RICHARD PYLE: Steve was asking is there any way we can sort of define what exertion levels are.

NEAL POLLOCK: The problem is we are back to how long is a piece of string. You cannot really quantify this. It depends on diver skill, readiness, so much, the equipment. As low as practicable made sense to me. You are trying to keep people from not overworking.

STEVE SELLERS: Neal, I think in a perfect world we would be able to. But I am fine with adding back that other piece that is not there.

DAVE PENCE: Last sentence simply read "management of diver exertion should be considered as part of dive planning."

NEAL POLLOCK: How about optimally? I think there is space in here.

RICHARD PYLE: Just to make sure I understand, is it worth asking the question does anyone disagree that there should not be excessive unnecessary workload? In other words, we all acknowledge that certain underwater tasks involve workload. That is, to me, where the "as practicable" comes in. Certain tasks require workload. We cannot get around that. Our recommendation is not to avoid those dives. What we are saying is, to me, the "as practicable" basically means trying to -- when you do not have to exert, try not to.

NEAL POLLOCK: We had a few hands up.

MARTY McCAFFERTY: I am hearing a lot of overthinking of these concepts. Everybody understands what exertion means. And it varies from diver to diver. So you cannot possibly account for all that. I am going to get exerted a lot sooner than John here. You are going to last a lot longer on a dive than I am, plain and simple. Do not overthink these things. I think the language is pretty clear. When you start trying to make it as specific to every possible contingency, it is not going to work.

DAVE CONLIN: Thanks, Marty. I agree with Rich. A case in point that we saw during one of the presentations, Phil chose to forego closed-circuit when he was going to go down and do a known physically difficult dive. That is what we are talking about.

SUSANNA PERSHERN: To go into the record, I would like this point discussed in the mixed teams briefing or open-circuit/closed-circuit. I am not talking about changing this, but I think that elevated workloads compared to your open-circuit buddies needs to be discussed in part of mixed team.

NEAL POLLOCK: That is a great point, but by saying it this way, we are saying as part of dive planning for every dive. To me, this is a solid umbrella statement.

DAVE PENCE: A question regarding the last sentence. As that is currently written, does that discourage Rich from engaging in moderate exercise?

NEAL POLLOCK: You could see it that way but I think there is room to maneuver. I view obligatory workload and a more limited intentional exertion for decompression as different. But you are right. This might come down to wordsmithing. I think we are at that point unless there is anyone who argues with the concept. We are trying to make sure that people are aware that physical exertion carries a risk, but still allow some room for thoughtful practice. I think we can work it out with wordsmithing. Anyone have a problem with that? No. Accepted.

Next:
"A switch from helium to nitrogen-based diluent during decompression is associated with a small increase in the risk of inner ear DCS. While this does not absolutely contraindicate diluent switches, in the majority of circumstances, decompression safety may be best served by remaining on a single diluent."

MARTY McCAFFERTY: I would like to know what the data show in terms of numbers of scientific divers being afflicted with inner ear DCS?

SIMON MITCHELL: Marty, I do not think there is any data about scientific divers, but there is a fairly strong body of anecdote from the diving world in general, technical divers, military divers, commercial divers, about inner ear DCS onset while still decompressing in temporal relationship with diluent switches. And on that basis we looked for a plausible mechanism, which we found. So when you add those two things together, it is pointing to the fact that diluent switches may be responsible for these problems. Now, this statement has been worded deliberately, no absolutes in there, but to reflect the emerging knowledge. And I think it is a reasonable response to that emerging knowledge. It is not saying you cannot do it. It is not saying you must not do it if the circumstances arise where you think it is a good idea for some reason. Like you run out of diluent and you have to go to something else. But I think it is reasonable. You will never have data specifically for scientific divers.

RICHARD PYLE: Personally I would be a little more comfortable if it was softened a little bit by removing the word "absolute." Just say, "this does not contraindicate diluent switches."

NEAL POLLOCK: "Contraindicate" alone actually strengthens it.

RICHARD PYLE: That is a good point.

NEAL POLLOCK: We added that in. This is intentional.

RICHARD PYLE: It does not contraindicate.

SIMON TALBOT: What about preclude?

SIMON MITCHELL: Preclude is fine.

NEAL POLLOCK: So do we want to keep the absolutely?

SIMON MITCHELL: Absolutely preclude diluent switches.

NEAL POLLOCK: That is good because this morning we were trying to get rid of contraindicate, and now it looks like we have done it. So while this does not absolutely preclude diluent switches.

LIZ KINTZING: I have a question for Simon. So this information that you have, is it always just a nitrox mix they are switching to or is it a trimix with a higher amount of nitrogen? So say they are on a -- I know you hate it -- but 10/50 just comes to my mind. And then they switch to 15/55 or 40/20 or something. Are they still having the issues there or is it when you go to just the nitrox mix?

SIMON MITCHELL: Nobody really knows, but why would you want to do a dil switch like that?

LIZ KINTZING: Only if you are on OC, you are bailing, right? I am confused.

SIMON MITCHELL: This is really for rebreather diving. Gas switches on open-circuit are always going to happen. There is no question about that. No one is saying you have to stay on trimix all the way to the surface. We need to restrict this to rebreather diving. It is not the intention that you cannot switch gases in open-circuit diving.

----- break in recording

NEAL POLLOCK: Safe source switching. We left this open. What is the concern on this one? Or maybe it is because we did not get to it. This is open for discussion. Who has concerns they want to raise?

PHIL LOBEL: So are we mandating then that we have to have these integrated mouthpieces that can switch between open-circuit and closed-circuit?

NEAL POLLOCK: I would not use the word mandate, but recommending.

PHIL LOBEL: Because I think for some circumstances, many of us just working in shallow water, not under extreme duress, normal evolution setup that I am using now is easy to turn off and put on another one. I think we have to be a little careful about the circumstances that might be most appropriate for this.

ROB ROBBINS: My concern is that, again, I think the biggest issue we are going to have are with freezing.

NEAL POLLOCK: Right. Operational need.

DAVE PENCE: I tried to take that into account. There is nothing here that precludes you from having second stages on your supplies. This simply says that in a normal circumstance the diver can quickly switch to something without having to juggle mouthpieces in front of their mouth and risk either flooding the loop or compromising their airway, and that a rescuer can accomplish that same thing.

RICHARD PYLE: It kind of seems to me that whatever language comes up with the full face mask, strappy kind of thing fits into here. They both really are focused on the situation of the unconscious diver.

NEAL POLLOCK: This is not necessarily about the unconscious diver. Right now let us table it. We can come back to it.

LIZ KINTZING: We are tabling a number of things.

NEAL POLLOCK: We are, but we have a lot to get through. We have about half a dozen that we still have to get to for initial discussion. This one I think we accepted as mom and apple pie, did we not? There is a problem with this one?

RICHARD PYLE: This one was only on the table because we thought it was so obvious it did not need to be included. That was the issue with that one.

NEAL POLLOCK: Okay. Let us table it for now.

JEFF BOZANIC: Prebreathe.

DAVE PENCE: It is not just the oxygen control systems. It may be the CO_2 monitor or the temp stick. It may be any controller monitor system.

NEAL POLLOCK: You are right.

JEFF BOZANIC: Just change the word "oxygen."

DAVE PENCE: Just take the word "oxygen" out.

NEAL POLLOCK: Do we want to say "control and monitoring?" Because it is actually not control; the temp stick does not control anything. I think this covers it. "It is recommended that manual and negative and positive tests should each be maintained for a minimum of one minute."

PHIL SHORT: Some platforms in use in the room you cannot do a positive check on. So it is platform-specific. Follow the manufacturer's guidelines. It is unit specific what you have to do to precheck the unit. Some of the platforms being used here you cannot do that.

JEFF BOZANIC: Just put in "when conducted, it is recommended."

NEAL POLLOCK: The group wanted guidance on how long should they hold that for.

LIZ KINTZING: When unit specified.

NEAL POLLOCK: I think Jeff is right. "When conducted, manual negative and positive pressure tests should be maintained for a minimum of one minute." Do you have a problem with that?

PHIL SHORT: I am just wondering why a lot of these points seem to be rewriting what is in the manufacturer manuals already.

GREG McFALL: Because in some cases they are not.

RICHARD PYLE: I want to echo that. I think almost every point we are coming up with is covered by at least one manufacturer's recommendation. And I think what we are trying to do is either amplify what manufacturers do or provide our impression of what a good best practice is when manufacturers have different policies and fill in gaps. So I do not think we should discard something just because some manufacturers or even most manufacturers cover it. I think some of these points are worth maintaining.

DAVE PENCE: I am going to play devil's advocate, not as to whether or not negative and positive tests should be done when appropriate. But what is magical about one minute. And the reason for that is for example, we do full build. We do our hardcore negative and positive tests. We transport the equipment. We put it on the boat. And before we put it on, one of the first things we do is we ensure that systems still have integrity. Those secondary tests I do not necessarily feel have to be a full minute. Are we setting something up so that if someone does a 45 s test or 30 s test they violate the best practice guidelines?

NEAL POLLOCK: Yes.

LIZ KINTZING: Have you already done one already for a full minute?

DAVE PENCE: This says "should be maintained." Does not say when.

RICHARD PYLE: That did come up in last night's conversation. And the question is then what are you actually gaining by that 30 s test.

DAVE PENCE: Yes. I am pretty sure that in the transport process I have not had a hose torn.

RICHARD PYLE: A gross hose problem? So you do not care about what you cared about when you did the one-minute thing. You only care about when you had the bigger problem. That is basically what you are saying. Is that legitimate?

DAVE PENCE: You have a hose pulled off and it is floating past your face once you get into the water. I can just see us sitting on the dive boat doing that final pre-prep and all of a sudden it is another two minutes longer.

RICHARD PYLE: If I can just understand your point, what you are saying is there is some value to be gained by positive and negative loop tests that are shorter than one minute?

DAVE PENCE: Yes.

RICHARD PYLE: But then I think the point is at least there ought to be -- it is hard to wordsmith. I see what his point is, but then you also want to say a 30 s loop test is not all you need, just once for each dive, unless the manufacturer has a different --

STEVE SELLERS: Do you take care of it by saying "when initially conducted, when assembled?"

NEAL POLLOCK: Let me ask a different question. How many people believe this as a point should be eliminated? So it is still live; we are not seeing people wanting to eliminate it. Okay. So now if we add "when initially conducted," and if it is just wordsmithing at that point, do not worry about it. Is this a satisfactory concept so far?

JIM HAYWARD: I think I can answer this question myself. So, Rich, what you are saying to Dave, is it more prudent to do that 30 s test on initial assembly and the actually full minute test just before you splash?

NEAL POLLOCK: Does anyone have a problem with this either existing or in its current wording? Hearing none, we are going to accept it. By the way, I understood during the break some people were concerned over one. We flagged it and will bring it back. Please do raise any concerns. We do not want people leaving here feeling like they did not have a voice.

DAVE PENCE: General comment. I agree with many of the folks who are expressing concerns on different things here, that there may be operational considerations for a particular application where a best practice may not be applicable and we should recognize that as well, that these are simply best practices.

NEAL POLLOCK: I believe we can address that in the preamble. We will try to put it in the caveats. Next:
Mixed team training. "Open-circuit team members must be able to read PO_2, add oxygen, add diluent, and operate buoyancy compensator. Closed-circuit team members must have available breathable gas accessible to OC divers."

JEFF BOZANIC: I think that is asking open-circuit team members to do too much. You are basically training them how to run a rebreather. And I think that they need to be able to operate a BC. They need to be able to do a reasonable rescue. And a reasonable rescue in my mind involves shutting the mouthpiece, proving open-circuit air, and getting the person to the surface.

JOHN BRIGHT: Is the wording of this not also a little biased to the oxygen rebreather users in attendance as well?

BRETT SEYMOUR: I would agree with Jeff. In putting together what I looked at for mixed teams, and operational experience, I think the reading of the PO_2, the oxygen and the diluent seems a bit excessive for emergency response capabilities in that world.

SUSANNA PERSHERN: And adding onto that, the only thing that we ask them to be able to do is if you have a BOV, is to turn it on or off, open the loop or close the loop.

DAVE PENCE: My open-circuit buddies need to be able to identify and respond to life critical events in my absence. Do they have to be able to operate my rebreather? No. They need to be able to know that I have a problem. They need to have been briefed and trained to recognize an emergency situation and take basic safe practices in order to rescue or assist me.

MAURITIUS BELL: I think we have kicked this one around before just around other rebreather divers and so on, what course of action is best. And we are talking about open-circuit. I mean, I guess we could be talking about mixed gas open-circuit divers, but I am assuming the normal route would be we are talking about no stop, single tank, open-circuit divers diving with a rebreather diver. So if a diver goes unresponsive in the water, we are talking about CCR diver, the open-circuit diver needs to maintain airway patency. The next thing there is kind of going to Simon's paper, is either way you are getting the diver to the surface. So I always wonder if we start adding a lot of open-circuit diver trying to interpret what is happening on the handset, trying to add dil --

DAVE PENCE: They need to be able to detect there is a problem.

RICHARD PYLE: Just a general point. These are best practice guidelines. There is no authoritative value behind these. I would recommend changing all "musts" and "shalls" to "shoulds." I do not think we are in any position to dictate musts.

NEAL POLLOCK: You are right.

RICHARD PYLE: That would at least soften it a little bit.

PHIL LOBEL: The last sentence, "closed-circuit team member must have available breathable gas accessible to open-circuit divers," I think if you are in a situation perhaps that open-circuit rebreather has a pony bottle of their own that they have an alternative source and not necessarily incumbent upon the closed-circuit rebreather to have extra gases for their buddy. Because sometimes I might be diving. I want as minimum stuff on me as possible in 30 ft (9 m) of water. You have to have enough bailout for yourself and if the bailout is important, the open-circuit should have that too. I do not want to have that coupled there. I have a problem with that last bit.

NEAL POLLOCK: Although if you are in that shallow dive, you have got enough onboard bailout for that anyway.

SIMON MITCHELL: I was around when this was being generated last night, and I added my two cents worth, which included those points about reading PO_2, adding oxygen, adding diluent. And the reason those are there is that there is a guideline for rescue of an unresponsive rebreather diver who has a mouthpiece in their mouth published by the UHMS. It is out there in the scientific literature. And I can pretty much guarantee you that if there is an accident, someone will go and look at that guideline and interpret what happened in terms of that guideline. Now, the guideline was written for rebreather divers diving with rebreather divers. It was not the intent of the guideline that all open-circuit divers should be trained in these methods if they happen to be in the water anywhere near a rebreather diver. However, what you have to remember is you are an official organization and you may be sanctioning an open-circuit diver to be the buddy of a rebreather diver. And I am just letting you know that these guidelines are out there. And in order to be able to fulfill the recommendations in those guidelines, those are the things you need to know. Now, if you make the choice not to require an open-circuit buddy of a rebreather diver not need to know those things, that is fine. I personally do not have a problem with that and I would dive with someone who did not know those things, but I do think there is a vulnerability there, and I think you need to think about that.

SIMON TALBOT: I just wonder why people see that as a problem. We do that with our open-circuit divers all the time. We practice rescues with them sometimes. They just have to know what it says and how to use the things that are important.

DAVE KUSHNER: I agree with Simon and Simon. It is hard trying to simplify things, but I think I would be happier if there were a clause in here that says the open-circuit diver must feel comfortable with the rescue of a rebreather diver. That is because you are dealing with variation in people's comfort level. You are putting somebody in the water that does not have the training on the unit. For somebody dense like me, I might want more explanation to feel like I can actually do the rescue and know how things work. So I think what you are dealing with is a high variability in diver comfortability from the open-circuit going to the closed-circuit. And I also still think that we should get divers that do not have any closed-circuit experience to weigh in on this and put them in situations and get some of that feedback.

BRETT DODSON: I was going to say that I agree in a team scenario practicing and working, that is not something that a lot of us are afforded when we have mixed teams. The idea of if you have dedicated OC support, that is a different scenario than if you have a need to put those two teams together. And what is the level of information that an OC buddy needs to effectively rescue me in a situation where things have gone wrong.

STEVE SELLERS: This is to Phil's comment. I think the point that was being made was, yes, there could be bailout for the CCR diver, but it has to account for the open-circuit diver if he is diving with a CCR that is not carrying an offboard bottle. I think you can modify that statement that just says it has to be available. It does not necessarily have to be carried by. "CCR team member should have available," that says to me that they have to carry it.

GREG McFALL: To me, this is the minimum. This is what you need to know in order to operate as a mixed team. And if you cannot do that, then perhaps the best practice is not to mix teams with open-circuit and closed-circuit.

JEFF GODFREY: I think a wording change on that would be "open-circuit team members must have emergency breathing gas available or immediately accessible." Or something like that. I do not feel like the onboard gas that I carry is available to an open-circuit diver so we have never allowed -- we have always required that closed-circuit divers carry offboard bailout bottles when diving with an open-circuit diver. But I can see that if the open-circuit diver is carrying his own offboard, then maybe that is okay for shallow dives, where onboard bailout is appropriate for the CCR diver. Just by making that little change, does that work for you, Phil?

PHIL LOBEL: Yes. I just do not want more junk.

DAN MONSON: I wonder if you might change it to say that the OC team members should be able to recognize life-threatening situation and take appropriate action to rescue the diver. And it might be that recognizing life situation is those things or it might be one of those things that he can see or whatever mechanism that can alert him that you have told him about. And it could be all these things or it could be, you know, a light or alarm. And then he knows how to deal with them. I mean, just in a general sense.

SIMON MITCHELL: That is even more complex. That is asking the open-circuit team members to be a rebreather diver. And I suspect that that is too complex. I think that one of the things that might improve this is if we were a little bit clearer about what we mean by open-circuit team members. This may be me not understanding what you guys are thinking, but to me, this knowledge is only important if you are the actual buddy of a rebreather diver. If you have got two rebreather divers diving together and two open-circuit divers diving together and you are all in the water at once, to me, that is not a situation where the open-circuit guys need to know anything about the rebreathers. It is just when you have an open-circuit buddy and you are a rebreather diver. That is when I think there is going to be a vulnerability if they do not have the knowledge that we are talking about here.

ED O'BRIEN: I agree with Simon. But I think we have also got to think about what our divers are going to be maybe diving in the future. As I see it, at least on my point, is they will be diving units like the Explorer, maybe the Poseidon 7. That should also be taken into account, maybe simpler units than many of the people in the room are diving now.

JESSICA KELLER: So if a wordsmithing thing could be done, at minimum, OC team members should be able to operate the buoyancy compensator device and close the loop, and if possible be able to read and do the rest, but separate it to the basics. And then if they can do this, that is great, but it is not the minimum of closing the loop and knowing where their inflator is.

MAURITIUS BELL: I think Susanna said this earlier. We have a bunch of things in there, but we need to throw in manipulation of the BOV. It is not in there, closing the loop.

NEAL POLLOCK: We have heard a lot but are not making great progress on this one. Last word to Dave.

DAVE PENCE: On further consideration, I like the original language.

NEAL POLLOCK: Okay, we will leave it open. We will come back to it as time allows, and let us see if we can make some progress on some others.
Next:
"Cross-platform diving team members must have --

RICHARD PYLE: Get rid of must. Should have.

LIZ KINTZING: I think they wanted to include this one with the previous one.

JEFF BOZANIC: Keep them separate.

NEAL POLLOCK: I agree on separate.

DOUG KESLING: I would add the word rebreather. Platform can be interpreted as a variety of different things.

GREG McFALL: Cross-platform rebreather diving.

PHIL LOBEL: Just a general comment too. Seems like some of our, when we are referencing this, we are kind of dumbing it down. We are scientific divers. If the question is can an open-circuit diver learn the closed-circuit and stuff, we should not be diving in this work mode. We should have a higher expectation of all our divers being smart enough to learn these things. If they are not, then we should not be diving in those mixed modes.

LIZ KINTZING: I think we are trying to leave it open to cover a whole variety of different environments.

PHIL LOBEL: You have got to be smart.

JEFF BOZANIC: The only comment I would make to that is it takes me six hours to take an entry-level, experienced, open-circuit diver and teach them enough to be able to monitor PO_2, interpret cell differences, add gas and diluent.

NEAL POLLOCK: So it can take time. Does anyone have a problem with this one? If the only problem was the desire to put it with the other one, which is now pretty messy, let us just skip that.
Next one:
"Proficiency should be documented with a minimum of 12 rebreather dives and a minimum 12 hours underwater time annually. Dives to count for proficiency will be no less than 30 minutes in duration."

PHIL LOBEL: So 12 and 30, that is half the time of the 12, right?

NEAL POLLOCK: No. What that is saying is you could do a bunch of dives in three hours but you cannot count a dive of one minute.

PHIL LOBEL: You have 12, 30 min dives, that is not going to be 12 h of diving?

NEAL POLLOCK: The final sentence says, "no dive shall qualify unless it is of 30 min duration."

PHIL LOBEL: But it says a minimum of 12 h underwater time. It should be a minimum of six hours.

NEAL POLLOCK: The elements are separate. You need a minimum of 12 dives and a minimum of 12 h. For any one dive to qualify, it has to be at least 30 min. All separate elements.

PHIL LOBEL: Why has it come up with 12?

RICHARD PYLE: I think it would be helpful to break this into two points of discussion. One is the notion of having a best practice recommendation about number of dives and/or number of hours. And then the other is what those numbers should be. And so I do not know if you want to parse that apart. First find out whether we all agree we should have something about this, and then we start arguing about the numbers.

NEAL POLLOCK: If you remember, the reason we put this up when we were talking about it last night, we did not have any of the numbers written in stone. We just put them in here as place holders. And so that is open to debate. I think it is valid to have a minimum duration time as opposed to the four 10 min dives in an hour.

LIZ KINTZING: I thought we were going to combine this with the workup dives, make it an and/or thing. And the other thing is that standard is nowhere. That is not anybody. NPS says more. AAUS says less.

PHIL LOBEL: I think just to say we have to have this workup dive. Because if I go without 12 dives, do I have to take the course over again? I think we have to have some explanation. If you have not done a certain number of dives, you have got to work up to regain your proficiency, not necessarily starting from scratch.

JOHN BRIGHT: Will it also be prudent to differentiate something like dive conditions? Something like, is it satisfactory to spend 12 rebreather dives 12 hours underwater in a pool just to maintain your proficiency versus engaging in environments or conditions that you would be expected to work in?

NEAL POLLOCK: The pool thing could get ridiculous really fast, but appropriate environments, yes.

DAVE CONLIN: John, just to address your comment, I think that is a DSO judgment call.

PHIL SHORT: Twelve hours of sitting on the bottom doing nothing is irrelevant. It is skills maintenance. Can you deal with an emergency situation even if it is just as simple as bailing out off the rebreather getting yourself to the surface? So you go and sit and do two six-hour dives. This does not assess proficiency.

NEAL POLLOCK: Okay. We are going to leave this one for now. We have two left. "Depth progression and unsupervised operation require demonstrated diver competency." The concept is there, but it has no detail. Should we say something like this as part of the mom and apple pie comments out of this workshop or is that too simple for people? And the second one, which we can consider paired, but I think people preferred this a little bit. "Pre-operation workup dives are recommended to establish diver competency."

LIZ KINTZING: We were going to put that with the other one.

PHIL LOBEL: Are not all dives supervised? Every dive has got a lead diver.

NEAL POLLOCK: I do not think you can say every dive is supervised.

PHIL LOBEL: So if everyone is underwater, it is unsupervised? I think we have to define that. Because, to me, every dive has a dive plan. Every dive is supervised by somebody in control.

JASON NUNN: I propose that we leave it the way it is and leave it up to the Diving Control Board to determine what constitutes proficiency and things. A couple hours in the pool might be good enough to go and do some shipwreck mapping at 30 ft (9 m). Whereas, you are definitely going to need a couple workup dives to do something more deep and complicated.

DAVE PENCE: There is already a statement that is more involved than this one in the AAUS standards.

RICHARD PYLE: The reason I think why this was separated out from the proficiency thing was in acknowledgement that pre-dive workups are highly specific to the particular thing you are pre-dive working up to. And so it was too hard to codify that in any kind of general best recommendation. However, we have a preexisting set of 12 dives in the AAUS paradigm annually for just a sort of chronic, ongoing proficiency maintenance. And several presentations over the last couple of days talked about that being inadequate for rebreathers. Which is why we separated them out into two separate points, one that had numbers, one that did not. I do not know if that is still relevant now. I just wanted to give that context to this conversation.

LIZ KINTZING: How about, this would be combining the two, but it would say something like if more than eight weeks, or whatever number we decide to pick, has lapsed since your last rebreather dive, then pre-mission or whatever you want to call it workup dives are suggested or should be done.

BRETT SEYMOUR: You are talking about best practices here. And, you know, AAUS might want to go a certain way. The NPS might want to go a certain way. All of these organizations have policies that they adhere to. If you leave it soft, then like Jason said, it is an organizational decision that is left. We have language that tells what pre-op is going to be and what duration is. We have established that. From a Park Service perspective, I do not feel like I need this discussion per se. So as a best practice maybe you do not get into the weeds, which I feel like we are. This is a multi-agency organization. Leave it to the institutions to figure out what is best for them.

NEAL POLLOCK: If we have the umbrella statement saying that currency, proficiency, and activity are important parts of this process. We can wordsmith something like that out of these simple ones. Because it does not sound like we are easily going to get to numbers.

RICHARD PYLE: I have a question for the group. Do we think that rebreathers, because of their technical nature, have different requirements from open-circuit in terms of proficiency and workup? Part of this is best practices that are focused on rebreathers as opposed to, "do not hold your breath while you ascend" kind of rules. My question is if there is a rationalization that rebreathers have different kinds of proficiency or workup requirements than open-circuit does, then it is worth including them in the best practice statement to amplify that point. But if we feel that these are general things that may be softened and generalized. I am actually asking the group do we all agree that rebreathers have special considerations for proficiency.

JEFF BOZANIC: I think they do. Unfortunately, I think that the platforms are significantly different in complexity, that that number varies from one system to the next. And we are not going to get the firm numbers because we are talking the Explorer versus the Sentinel. It is going to be two different numbers.

GREG McFALL: Maybe our time would be best spent with this body of people, going back to what Phil was saying. What does this body define as proficiency, and just leave the numbers aside. Because John is right. It is going to be up to the individual organizations DCBs to determine what that number is. So what does it mean to be proficient?

NEAL POLLOCK: So, we need a definition of proficiency.

RICHARD PYLE: That just comes back to what I was trying to say. The essence of proficiency is quite different from open-circuit versus closed-circuit. In open-circuit it is really about cycles and hours. Whereas, in closed-circuit it is like Phil said, there is drilling and skills. It is a different kind of paradigm.

JEFF GODFREY: That goes back to what Jason said also. I think identifying proficiency levels should be part of the dive planning process. So by defining proficiency here we will probably get to something better by identifying it for the diving control boards.

NEAL POLLOCK: We are at a little bit of a crossroads here. We are starting to look at things that could take a lot of time. We have got 45 minutes left. And we are at the back of our list, but we had five or six items that we wanted to pull back from the deferred list. So you folks can guide what we want to do. We also have at least one that we pulled back based on comment during the break. Let me just show you where we are at from our deferred list. The things people wanted pulled back, actually a new one was added, training and managed task loading. In a way that goes back to proficiency. If we add that proficiency one, tied down, this one would be taken care of. "Information on CCR support and requirements for non-CCR supervisors." And you can read through the list of white ones. Multi-institutional operations, post-dive checklists, which units and program use, and then when to change scrubber guidelines. Those are all ones that are on the list. We need to decide how to best spend the next 45 minutes. We can try to work on these. We can try to identify key issues that would best be resolved while we are all together. What is recommended here?

JEFF BOZANIC: Two of these might get handled really quickly if we just put the post-dive checklists on top of the pre-dive checklist one previously, which would ignore the incident reporting, but it would at least get the concept of post-dive checklist needing to be included. The other one is when to change scrubber and guidelines on storage. We do not have enough data to be able to answer any of that, nor do any of the manufacturers. It is really important because a lot of people do it. Put that on our research list of research priorities.

NEAL POLLOCK: And that one, if you can trust a little wordsmithing, we can use that as a research priority very easily. So that text is pretty simple. And for the post-dive checklist, when you are saying on top of, are you saying integrated in?

JEFF BOZANIC: Yes, just where it says "build, assembly, pre-splash," just add post-dive checklist.

RICHARD PYLE: As a fourth.

DAVE MONSON: I just wondered if we take this opportunity for us as oxygen divers, one quick question on when to change the scrubber. Is there any reason, I know this whole deal of what the testing is like and what it means, we do not know what that means. Is there any reason for us to recommend in our own documentation that we use scrubber less than what the manufacturer guideline is? We have a three-and-a-quarter-hour limit on the scrubber and for some reason we have two hours in our limit as to how long we are going to use a scrubber pack, and I do not know why we are doing that. Is there any reason why anyone else -- I think there is a lot of conservatism already built into that number.

NEAL POLLOCK: Anyone? Insights? I have no idea what the rationale was.

DAN MONSON: So there is no reason to go less than the manufacturer?

NEAL POLLOCK: Well, it would be nice to know who came up with that or why, whether it was just for conservativism. Not hearing any insights here. What else do people want to comment on right now?

JIM HAYWARD: I was the one that championed the multi-agency one. It seemed like the ideal audience, but time does not allow. So take the weight off of that.

NEAL POLLOCK: Okay, multi-institution is deferred. Next: Research priority: "Collect, review and publish data evaluating when to change scrubber." Any concerns with this concept? No. Then we will wordsmith.

Now, the person who wanted the information on CCR support and requirements for non-CCR supervisors felt this was a real liability issue if we did not address this. Thoughts?

RICHARD PYLE: Is that framed as a best practices or is that something that somebody ought to write a sort of summary on for the proceedings? I am not quite sure how to frame it as a best practice?

NEAL POLLOCK: If I understand correctly, they wanted guidance on that. It was tough. That is why we deferred it. We did not have a solution.

UNIDENTIFIED SPEAKER: I am one of these guys. So, you know, multiple ways it could be done. It would be easy enough for me with limited knowledge to look at best practices that are out there in addition to the dive plan that the group may actually supply to me. It would be an easy enough one which you all are putting out as a best practice to put a check off. The other one would be through the AAUS manual and the rebreather section. Although it may not be part of my manual since we are not doing dives like this on a regular basis, I can look at it and go through and again hit the points and check as an additional piece of the dive plan that they submit. So I am not sure that, my personal end of it, is I think I can find the information.

GREG McFALL: This is something that we are going to be tackling next month. We are having a unit diving supervisors conference. And part of the agenda of this conference is to kind of dispel some of the myths about rebreathers and make our unit diving supervisors more comfortable with CCRs on their platforms. We might be able to tackle some of this and come out with some, what should they know kind of situations.

DAVE PENCE: I submit that the best practice is that the supervisor, especially the DSO, needs to be conversant in the life support technology that is being used regardless of what that life support technology is. So if you are building a rebreather program, it is incumbent upon you to start from the top down in terms of informing your DSO, your DCB, and your supervisors. That is a matter of strategic planning for the institution. But the best practices is that the DSO and the supervisors need to be the subject matter experts that you are working from.

RICHARD PYLE: Might it make sense to reframe this along the lines of the full face mask and the CNS? In other words, sort of a research topic. It would be good if someone assembled a white paper on basic information about rebreathers in scientific programs to be available for DSOs who are new to that topic. In other words, there are books written by guys in this room and there is all this information. It might in the scientific context make sense to aggregate that and do a summary document for DSOs wanting to get their head around it.

NEAL POLLOCK: So am I hearing the proposal to call this a research priority?

RICHARD PYLE: Potentially.

JEFF GODFREY: I think we may have lost context on this one. Is Eric in the room? He brought this point up. And it primarily had to do with DSOs in marine labs that do not have rebreather operations ongoing but still may have a supervisory role over visiting scientists that are bringing in rebreathers.

NEAL POLLOCK: How many would like this to be put in the standard wording we have got for research priority? I do not like it as research myself.

DAVE PENCE: Action item.

JEFF BOZANIC: Policy development.

NEAL POLLOCK: Can you trust us to wordsmith this one, that we will more or less call it policy development, develop guidelines, for the purposes of this? Okay.

JEFF BOZANIC: Let me ask one question. Do we want to have a paper that is authored for these proceedings on this particular topic even though it was not presented as a paper here?

NEAL POLLOCK: I do not believe so. Proceedings are normally limited to papers that are delivered. The authors can expand on the theme, but the theme was presented in the meeting. This would typically exclude topics that were not presented at the meeting.

JEFF BOZANIC: I know normally you do not. That is why I am asking the question. It is being discussed.

NEAL POLLOCK: And the discussion will be captured, but not as a paper. Could we do it? Sure, but I am not convinced that it is necessary or appropriate.

DOUG KESLING: It could be added into the operational, but it needs some boilerplate to kind of frame it.

JEFF BOZANIC: I am just raising the question. I am not promoting it. Some of these things we could probably do if we had another couple of hours with three or four people here. We just do not have that time.

NEAL POLLOCK: If we are talking about a real short thing and it is not a full paper, I am happy to see it go in the discussion. The other thing we have to remember is that we are going to have enough cat herding to get the papers we have. If somebody hands in a paper that is ready to go, it is more likely to get a more positive response than someone who says, let me think about this. I might get it to you in six months.

DAVE PENCE: Similar to the expert group that reviewed rescue standards and published a paper, can we simply make a statement that we need to identify a group of qualified individuals to write an advisory paper on this topic?

NEAL POLLOCK: We could. The question is whether it is a priority. We now have six research priorities and one likely workshop priority. We need a champion.

GREG McFALL: I can certainly write it from NOAA's perspective, but I think it has a larger context. So by a show of hands if a couple of other people would like to form a small committee to get that done from your perspective, I would like some help on it. Okay. So Simon, Dave, Les and Jason.

NEAL POLLOCK: So we will encourage small group formation, policy group. Small group to evaluate. And this is led by Greg McFall at this point in time. We had one that we accepted that some individuals wanted back. "Rebreather O_2 sensors should be calibrated in accordance with manufacturer recommendations or at a minimum every time the absorbent is changed." Can we resolve this?

PHIL SHORT: I agree with Susanna's comment. What is the relevance of absorbent change? If you want to add anything to manufacturers' recommendations because the general consensus seems to be they are quite vague and some manufacturers do not even have any. Most of the calibration systems on many of the platforms used require electronics. So a lot of the manufacturers say the batteries are changed or if the system is recharged, then you must calibrate after a battery change or a recharge. Personally, I do not think you should add anything other than "in accordance with manufacturers' recommendations." I do not see any relevance whatsoever with the absorbent issue. The power issue may be more relevant.

RICHARD PYLE: As I said before, I am confused about the absorbent thing also. But I wonder if this would not be clarified if it did not begin with "in the absence of manufacturer recommendations, rebreather O_2 sensors should be." In other words, defer, but also acknowledge the point that has been raised that not all contingencies are covered by all manufacturers.

NEAL POLLOCK: Let us start with a fundamental question. What are we gaining from this point right now? We are perhaps highlighting one issue, but is that one that needs to be highlighted now? We are hearing some people who say no. Do we gain anything materially out of including this?

PHIL SHORT: One thing. There is been a lot of complaints about certain manufacturers and their manuals do not tell you what to do. Well, if that is your platform, ask them. Get it in writing. And then follow it.

RICHARD PYLE: To amplify Neal's question, what are we trying to say in the best practices here that needs to be said? And I am not quite sure I get that. Where is the gap in knowledge that the manufacturers are not filling or whatever else that we feel needs to be filled with a best practice statement?

JEFF BOZANIC: I was thinking the same thing. My comment is the problem is not sensor calibration. It is sensor validation at PO_2s above 1.0 seems to be where the gap is. And I think that is one of the things we talked about.

NEAL POLLOCK: Now we are back to Doug's point, which we added. We are going to go on to that next. So we will go on and talk about cell testers. Is this one that we can delete? How many people believe this one is not serving a valuable purpose and can be deleted? Right now that is looking like a majority. How many people believe this should stay and be worked on? That is zero for the stay and work on. Okay, it is cancelled.

This is one that Doug Kesling brought up. Doug, for the record, do you now want to make your point?

DOUG KESLING: I am just wondering whether people are using cell tester and the validity of their test and whether it is something that should be incorporated as a best practice or just ignored?

RICHARD PYLE: Are you specifically asking for a current voltage limit test or can you elaborate on what you mean by test?

DOUG KESLING: We had a period during a Puerto Rico cruise where availability of cells were limited and the distributor was not manufacturing them. And we were trying to figure out in terms of longevity of the cells and performance of the cells how do we ascertain the performance of the cells so a pressure pot test looking at the cell and measuring that to rule it in, rule it out. To my understanding, it may not give you what you're looking for, that even with that positive test it may fail within minutes during the dive.

RICHARD PYLE: To clarify, the question is with regard to the linearity of the oxygen sensor above 1.0 ATA. That is the crux of this one. I can answer, yes, we do. We do what we call a hyperoxic linearity test. It can be done. But that is done during the dive, not before the dive.

SIMON MITCHELL: This is a question that the technical diving community have been wrestling with. And it has been dealt with in forums like this and I guess by people who are considered to be the expert in cell technology, which I am not. I am just relating their opinions. The pressure pots are useful, but the problem with them is they simulate exposure to high PO_2 or provide exposure to high PO_2 for as long as you do it. If you just stick your cells in there for a half an hour and they hold voltage, that is does not tell you what is going to happen in an hour or in the more challenging conditions of a rebreather platform. So it does not rule out the possibility that your cells are going to drift out of whack as the dive progresses. And this has been seen on many occasions. There are many accidents where the cells are nice and confident at the start of the dive and then over time drift out. In fact, Paul Raymaekers who manufactures a rebreather, believes that the best time to evaluate the health of your cells is to do an oxygen flush at the end of your dive. That will give you more information than anything that you can do before you dive. So I just put that out there. I have actually got an oxygen cell tester, and I quite like using it, but I do not kid myself that it tells me that my cells are going to be fine for the whole dive.

PHIL SHORT: I agree. I think the oxygen cell test has its use, but it has the same drawbacks as the prebreathe.

DAVE PENCE: I think that hyperoxic oxygen cell validation is one of the true black boxes of what we are doing, and for all the reasons that have already been stated. If you use a pre-dive checker, you get a snapshot in time that might not be applicable in the everyday environment. Just everything that Simon said. It is an area that I am also in agreement. I religiously do an oxygen flush at the end of the dive. The cat is out of the barn for that dive, but if I am doing day after day of diving, that is the time to be looking at my cells to see if they are okay for the next day.

RICHARD PYLE: Would it be worth framing this as a research priority? To find out what the reality is out there in terms of actual incidents of these kinds of problems.

DAVE PENCE: Not just cell testers, but cell validation protocol either manual or automated.

DAVE CONLIN: And maybe individual cell failure rates per use. Maybe that comes under the data that we are collecting.

NEAL POLLOCK: I do not think we want to be too specific with research initiatives. We have the concept of cell testers and validation protocols. I do not think we have to enumerate.

MAURITIUS BELL: When we were talking about training and so on, that was one of my questions. That is something we do religiously on our dives at 30 ft (9 m). We always spike our PO_2 and ensure that we get a higher reading on each of the cells and periodically do it throughout the dive. But I was wondering how much of a practice in our community and whether from a training perspective. We did not really hit too many of those.

NEAL POLLOCK: Most of the training elements were tabled in recognition of time constraints. We have worked through the rest of the list. What else do we want to accomplish as a group? I heard there were some comments that we have been skewed towards the more extreme end of the diving and not doing enough for the basic rebreather operations that might be common. If so, how should this be addressed?

BRETT SEYMOUR: I think that a good part of the philosophy is coming together. And like I think Nimz's point of multi-agency operations, that was what we were looking at, getting all these people in a room and how do we work. But I think there is a need to stress that some of that was missed in terms of presentations. So that might be considered a negative. But a positive is getting the people together and making the contacts. I would encourage ongoing exchange because I think that this is kind of the opening salvo, if you will, to continue this conversation. I feel like there were some presentations on some amazingly awesome things and presentations that had cross platform design - gas densities and decompression algorithms and modeling. But our operations are not going to 320 ft (98 m). We are looking operationally to extend bottom times. So looking at this conference through that lens and meeting with your people the information has been disseminated through that filter. Do not go back and say, oh, we have to calculate the gas density on every dive now. We do not. You have to establish a protocol and you have to live by that. But to encourage the continuation of the dialogue, remember those not going deep. The majority are more likely to be extending bottom time so scientists can work longer. I do not see it as a missed opportunity. I do not say that I am bummed out because I came and we did not get that. But I think there needs to be recognition that there is a large group of people who are just using the rigs operationally to do their work and not as an expedition based model.

NEAL POLLOCK: We will try to address limitations in the preamble text. We have accomplished a fair bit in this time, but it is challenging to get to everything.

RICHARD PYLE: Getting specifically to the inter-agency issue, which seems to be on the forefront of a lot of people's mind, it is not limited to outlier expeditionary diving. There are many examples of inter-agency and inter-multi-institutional diving. I wonder if it would be worthwhile for the people with experience in that to gather together some ideas, write them down either as an appendix to the proceedings or published somewhere else. Basically, to outline the issues and how they have been resolved on actual projects. If that is perceived by the group as being one of the important topics not covered.

NEAL POLLOCK: There is an AAUS meeting coming up. A good way to address holes in our progress or to make progress on needs that have been established is to present relevant content at the AAUS meeting. For example, documenting the closed-circuit oxygen rebreather diving activity relative to the CNS oxygen clock. This would be a good time to put out a paper summarizing techniques, shortcomings, issues, questions. You have got a lot of people you can talk to. We could get half a dozen papers into the AAUS proceedings to follow on our efforts here. That would be fantastic. We will produce one document, hopefully a useful one, but we need to build momentum. We should promote relevant special topics workshop for AAUS meetings. I am not speaking for AAUS, by the way. This is just me suggesting these things. But I think it would probably go over pretty well. Rick Gomez is smiling.

STEVE SELLERS: It just sounds very familiar to the strategic planning discussions that went on with the AAUS group over the weekend.

NEAL POLLOCK: Very good. Everybody wants to do things. We have the group that Greg McFall is going to put together. Let us encourage that group to develop a manuscript for the AAUS meeting. Likewise for the oxygen rebreather divers. Let us take some of the limitations of this meeting and generate some documentation to overcome them in the next six months.

LIZ KINTZING: Did we finish everything? What about the proficiency question that you said we are going to come back to?

NEAL POLLOCK: Yes. "Unit specific checklists should be used to ensure completion of essential" We added some text during the break. I thought everybody was comfortable with it.

JESSICA KELLER: I have a comment on that one. The diver familiarity, I had a conversation with Jeff about this. The issue I came up with is complacency. Checklists help with negating complacency. Jeff Bozanic is a little bit different because he teaches on this. But for other people when are you okay and blessed that you are familiar enough with this unit that you do not have to use a checklist?

PHIL SHORT: Never.

JESSICA KELLER: So I think that that should be taken out because you should always use a checklist to reduce complacency.

NEAL POLLOCK: In defense of Jeff, this is not saying the checklist goes away. It is saying it is more streamlined. I agree it is a slippery slope.

RICHARD PYLE: In that context, it does not specify what is in the checklist to begin with. Already the checklist is vague. It is just checklist generically. It is not saying fully detailed, paper and pencil checklist. It always seems like that last sentence is redundant because you could interpret the word "checklist" as you see fit.

NEAL POLLOCK: Should we take out that last sentence?

DAVE PENCE: If you look at other industries that have heavy-duty checklist traditions such as aerospace or aviation, that concept does not fly, I do not think, in those communities.

NEAL POLLOCK: No pun intended.

DAVE PENCE: Right. No pun intended. I would vote to take it out.

JESSICA KELLER: It also goes into it that as an institution we are held to higher standards than the recreational world. But the people who are more familiar with the units are also our leaders and our role models, and we want them to be using some sort of checklist so that the younger, junior members have a good role model to look up to. Whether or not it is an electronic checklist, it is always an assurance thing that we know that they are using it and it is easier to see that piece of paper.

DAVE CONLIN: The other part of the checklist is that they are not just for you. Checklists are for the institution covering your diving. If something happens, the first thing the investigator is going to say is, did the diver do their pre-dive checks, yes or no?

JEFF GODFREY: The only thing this last sentence does is recognize the difference between a training checklist and an operational checklist, and it could go away. I do not think it really hurts it. It may not even recognize it far enough. If you are not proficient on the unit anymore, you may need to go back to the training checklist just to recognize the difference between the two.

ROGER MAYS: Dave mentioned the airline industry. I do not know if everybody in the room is aware or not. The airline industry did not use checklists originally. They went to them because that was a way to greatly reduce accidents, incidents. From what I understand now, and Simon might correct me if I am wrong, but I understand the medical industry is heading towards checklists for the same reason. We need to do this.

SIMON MITCHELL: You are right. I have had a lot to do with checklists in the medical context, specifically in the operating room. Just like in the aviation industry, we have hard data that shows that the introduction of relatively simple, critical point checklists to operating room practice reduces mortality and complications. It is extraordinary. It is simple to do. It is cost effective. And those checklists do not change according to the experience of the operating room teams. It does not matter how many times you have done this procedure. You do the same checklist. So if that sentence is to imply any sense that as you get older and wiser, you can do away with the checklist, I am totally against it. That is a flawed concept. And that is exactly why you need checklists, for perceptions like that. Because it is the older, wiser people who start to make mistakes.

JEFF BOZANIC: The question I would ask Simon is what you hit right on the nail. Simple, critical mission checklists. And the problem we have right now is that none of our checklists are simple and mission critical.

SIMON MITCHELL: One of the problems here that I have never actually encountered in discussion of diving before is this difference between training checklists and operational checklists. My sense of a checklist is not the training checklist. It is a key point, critical step checklist of things. My unit is on. My oxygen is switched on. I have done a prebreathe. Those things are the critical things that I want on a little piece of paper that is attached to me that is laminated so I can look at it before I get in the water. That is what a checklist is. Not a 100 item sheet for putting your unit together.

JEFF BOZANIC: And that is the progression I talked about.

NEAL POLLOCK: The first part does not stop you from having appropriate or different checklists. There is nothing in the first one that goes against that. This first section is completely valid.

LIZ KINTZING: It just says checklist. It does not say it has to be written. It does not say it has to be 22 things long.

NEAL POLLOCK: Let us wrap up this discussion with a vote. How many vote to strike the sentence that is now highlighted? Very good; it is gone. We have one last one that is uncovered, the safe source switching. Can we do anything with this right now?

RICHARD PYLE: I would encourage people who have concerns with this language to express those concerns via email message to the full CC list and maybe precipitate a discussion.

NEAL POLLOCK: We are out of time. We will circulate a draft for review by this group. Thank you very much.

STEVE SELLERS: I am pretty pleased with what we were able to accomplish while we were here. I hope you got a lot out of it. I know I did. I want to thank all the presenters and Neal and Jeff and Greg and Dave and Brett, all the folks that have helped on the front end to help organize this thing, and our wonderful hosts here on Catalina.

(Meeting adjourned)

APPENDIX A
LIST OF ACRONYMS USED

AAUS	American Academy of Underwater Sciences
ADV	Automatic diluent valve
BOV	Bailout valve
BSAC	British Sub-Aqua Club
CC	Closed-circuit
CCR	Closed-circuit rebreather
CE	Conformité Européenne
CMAS	Confédération Mondiale Des Activités Subaquatiques (World Underwater Federation)
DAN	Divers Alert Network
DCS	Decompression sickness
DCB	Diving control board
DSO	Diving safety officer
EMS	Emergency medical services
END	Equivalent nitrogen depth
EUBS	European Underwater and Baromedical Society
ffw	feet of freshwater
fsw	feet of seawater
HSE	Health and Safety Executive
HUD	Head up display
IP	Intermediate pressure
IPE	Immersion pulmonary edema
IANTD	International Association of Nitrox and Technical Divers
MOD	Maximum operating depth
mfw	meters or freshwater
msw	meters of seawater
NAUI	National Association of Underwater Instructors
NOAA	National Oceanic and Atmospheric Administration
NPS	National Parks Service
NTSB	National Transportation Safety Board
OC	Open-circuit
PADI	Professional Association of Diving Instructors
RSTC	Recreational Scuba Training Council
SAA	Sub-Aqua Association
SCR	Semiclosed-circuit rebreather
SPUMS	South Pacific Underwater Medicine Society
SSI	Scuba Schools International
SSUB	Scottish Sub-Aqua Club
TDI	Technical Diving International
TSA	Transportation Security Administration
UBA	Underwater breathing apparatus
UHMS	Undersea and Hyperbaric Medical Society
USGS	United States Geological Survey

APPENDIX B
WORKSHOP PARTICIPANTS

Mauritius Bell
University of Hawaii, Hilo
Hilo, HI, USA

Gordon Boivin
University of Southern California
Los Angeles, CA, USA

Jeff Bozanic
Fountain Valley, CA, USA

Marc Blouin
United States Geological Survey
Saint Petersburg, FL, USA

John Bright
National Park Service
Lakewood, CO, USA

Les Burke
University of Maryland
College Park, MD, USA

Zach Caldwell
Nature Conservancy Hawaii
Honolulu, HI, USA

Eric Castillo
University of Southern California
Los Angeles, CA, USA

Scott Chapman
Monterey Bay Aquarium
Monterey, CA, USA

Dave Conlin
National Park Service
Lakewood, CO, USA

Paul Dimeo
Aquarium of the Pacific
Long Beach, CA, USA

Brett Dodson
Texas A&M Corpus Christi
Corpus Christi, TX, USA

George Esslinger
United States Geological Survey
Anchorage, AK, USA

Jeff Godfrey
University of Connecticut
Groton, CT, USA

Shawn Harper
University of Alaska, Fairbanks
Fairbanks, AK, USA

Brian Hauk
National Oceanic and Atmospheric Administration
Honolulu, HI, USA

James Hayward
University of California Berkeley
Berkeley, CA, USA

John Heine
National Science Foundation / United State Antarctic Program
Jacksonville, FL, USA

Bert Ho
National Park Service
Lakewood, CO, USA

Karl Huggins
University of Southern California
Los Angeles, CA, USA

Elliott Jessup
California Academy of Science
San Francisco, CA, USA

Jason Jones
University of Hawaii
Honolulu, HI, USA

Jessica Keller
National Park Service
Lakewood, Colorado, USA

Doug Kesling
Aquatic Training Systems
Wilmington, NC, USA

Mark Keusenkothen
East Carolina University
Greenville, NC, USA

Elizabeth Kintzing
University of New Hampshire
Durham, NH, USA

David Kushner
Channel Islands National Park
Ventura, CA, USA

Jason Leonard
National Oceanic and Atmospheric Administration
Honolulu, HI, USA

Phil Lobel
Boston University
Boston, MA, USA

Roger Mays
National Oceanic and Atmospheric Administration
Beaufort, NC, USA

Martin McCafferty
Divers Alert Network
Durham, NC, USA

Christian McDonald
Scripps Institution of Oceanography
San Diego, CA, USA

Greg McFall
National Oceanic and Atmospheric Administration
Seattle, WA, USA

Simon Mitchell
University of Auckland
Auckland, New Zealand

Shelby Moneysmith
National Park Service
Homestead, FL, USA

Daniel Monson
United States Geological Survey
Anchorage, AK, USA

Narineh Nazarian
Glendale, CA, USA

James Nimz
National Park Service
Key West, FL, USA

Jason Nunn
East Carolina University
Greenville, NC, USA

Ed O'Brian
Woods Hole Oceanographic Institution
Woods Hole, MA, USA

Dave Pence
University of Hawaii
Honolulu, HI, USA

Susanna Pershern
National Park Service
Lakewood, CO, USA

Neal Pollock
Divers Alert Network / Duke University Medical Center
Durham, NC, USA

Richard Pyle
Bishop Museum / Association for Marine Exploration
Honolulu, HI, USA

Rick Riera-Gomez
University of Miami
Miami, FL, USA

Rob Robbins
United States Antarctic Program/ASC
Denver, CO, USA

Steve Sellers
National Park Service
Lakewood, CO, USA

Brett Seymour
National Park Service
Lakewood, CO, USA

Gemma Short
Devizes, Wilshire, United Kingdom

Phil Short
Devizes, Wilshire, United Kingdom

Simon Talbot
University of Tasmania
Hobart, TAS, Australia

Joe Tomoleoni
United States Geological Survey
Santa Cruz, CA, USA

Daniel Wagner
National Oceanic and Atmospheric Administration
Honolulu, HI, USA

Benjamin Weitzman
United States Geological Survey
Santa Cruz, CA, USA

APPENDIX C
WORKSHOP AGENDA

REBREATHERS AND SCIENTIFIC DIVING

February 16-19, 2015
Wrigley Marine Science Center, Catalina Island, CA

Time	Duration	Presentation	Presenter
February 16			
1300 – 1330	0:30	Overview of scientific CCR program activity	Sellers
1330 – 1500	1:30	Accident overview/review	Bozanic
1500 – 1530	0:30	Break	
1530 – 1600	0:30	Rebreather evolution in the foreseeable future	Pyle
1600 – 1700	1:00	Respiratory limitation of CCRs	Mitchell
February 17			
0830 – 0900	0:30	Organization standards for scientific CCR	Kintzing
0900 – 1000	1:00	Operational practice for scientific CCR	Kesling
1000 – 1030	0:30	Break	
1030 – 1200	1:30	Emergency procedures and task-loaded management	Short
1200 – 1300	1:00	Lunch	
1300 – 1400	1:00	Biological impact of CCR & small team remote operations	Pyle
1400 – 1500	1:00	Mixed team operations	Seymour
1500 – 1530	0:30	Break	
1530 – 1700	1:30	Factors in decompression stress	Pollock
February 18			
0830 – 1000	1:30	Gear configuration (hands on)	Short
1000 – 1030	0:30	Break	
1030 – 1200	1:30	Decompression science: critical gas exchange	Mitchell
1200 – 1300	1:00	Lunch	
1300 – 1330	0:30	Oxygen safety	Godfrey
1330 – 1500	1:30	Diving the algorithms - dive profile review	Pollock
1500 – 1530	0:30	Break	
1530 – 1600	0:30	Progress summary and best practices straw man	Pollock
1600 – 1700	1:00	Best practices discussion	
February 19			
0830 – 1000	1:30	Best practices discussion	
1000 – 1030	0:30	Break	
1030 – 1200	1:30	Best practices discussion	
1200		Adjourn	

NATIONAL PARK SERVICE

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

DAN®

AAUS
AMERICAN ACADEMY OF UNDERWATER SCIENCES

ISBN 978-0-9800423-9-9
9 780980 042399 >