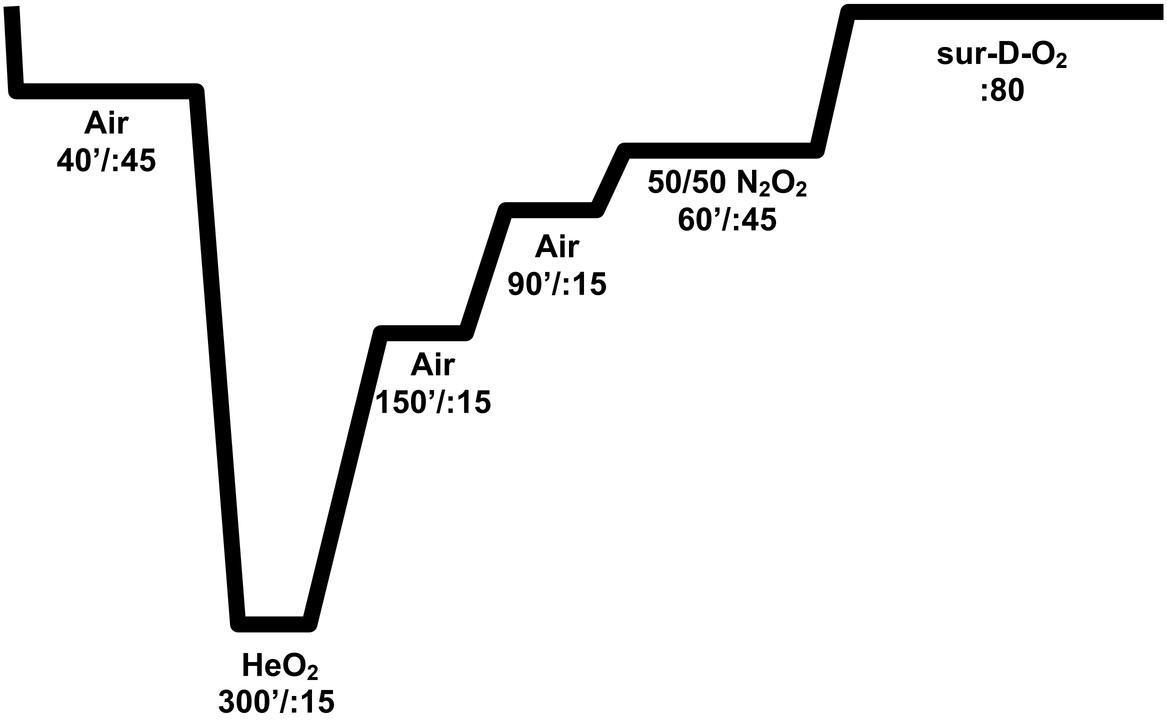
PROCEEDINGS OF ADVANCED SCIENTIFIC DIVING WORKSHOP



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Cover graph: 300 fsw multi-depth, multi-gas dive profile described by M.L. Gernhardt (p. 36).

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Acknowledgements

I wish to acknowledge and extend sincere appreciation to the Advanced Scientific Diving Workshop co-sponsors: Dr. David Evans (Smithsonian Institution), Ms. Barbara Moore and Ms. Karen Kohanowich (NOAA-National Undersea Research Program), Dr. Dan Basta, Dr. Steve Gittings, and Mr. Mitchell Tartt (NOAA-National Marine Sanctuaries Program), and Mr. William Dent, Mr. Steven Sellers, and Mr. Jeffrey Godfrey (American Academy of Underwater Sciences). This scientific diving workshop would not have been possible wihtout their combined support.

Many thanks to all the workshop speakers who helped immensely by submitting their manuscripts on time. The short turn-around time for the production of proceedings for a workshop of this size is unprecedented and could not have happened without the full cooperation of the authors. We take satisfaction in having assembled this espert cast of professionals who shared their expertise on this topic with the workshop. The international, interdisciplinary nature of this project is evidenced by the participation of colleagues from the recreational, technical, commercial, military, and scientific diving communities and the papers they presented. Participants from Scotland, Norway, France, and Switzerland has the opportunity to interact with colleagues from across the United States.

Smithsonian Institution staff who were very helpful during various phases of this workshop's organization and conduct deserve special recognition: Laurie Penland (Assistant Scientific Diving Officer) for her assistance with most of the complicated logistical aspects, Shelly Cole (Office of the Under Secretary for Science) for her assistance with participant travel and purchase orders, Stacy Cavanagh (Office of the Under Secretary for Science) for authorizing expenditures and keeping track of the budget, and Smithsonian Environmental Research Center Director Anson Hines for his support as Chairman of the Smithsonian Scientific Diving Control Board.

Finally, I thank my Workshop Co-Chair, Gene Smith, for his pertinent, advanced operational diving insights and support, and above all, pleasant willingness to ensure that this workshop and its proceedings become a model for those that follow. I enjoyed our collaboration and, from all indicators, have the sense that we succeeded in accomplishing our workshop objectives.

Michael A. Lang
Smithsonian Institution
Workshop Co-Chair

Welcoming Remarks

I offer you my welcome to the Smithsonian and am really pleased that all of you are here. This workshop agenda and the list of experts who are speaking and attending make it quickly apparent that the right mix of people have come together to discuss a topic that is important. I have to confess that I say important as an outsider. Those of you who knew me at NOAA know that I'm dreadfully claustrophobic and my maximum working depth is about the length of a snorkel. Once upon a time when I committed science as an oceanographer, this was not the kind of oceanography that I did.

On the other hand, I did spend a certain amount of time bouncing around on top of the Monitor, in the early days of trying to do some assessment and preliminary recovery work there and saw some really interesting diving technology that the Navy brought to bear on that problem. That's a nice recollection for a conference like this, that combination of programs and people with common technical interests and scientific goals getting together. In the Monitor case, it was NOAA and the Navy working at a National Marine Sanctuary, one of the sponsors of your event here along with the NURP program and the AAUS. I want to thank you for helping to pull this together. It was clear from that experience that going a bit deeper and using different technology was important for the people who had real problems to solve. The issues that come into Michael's office here represent a constant pressure to push the limits of what our scientists can do. Getting a group together like this to actually deal with those questions and figure out how we can go about doing our deep science seems to me to be exactly the right mechanism.

There are probably NOAA Diving Manual chapter authors present or certainly the work that all of you are responsible for was included as a collaborative effort, one that brings together people from a lot of different agencies with different specific missions or scientific goals. There is a real common interest in making the technology better, safer and more available to really expand where we can go and what we can do.

I underscore the safety part because, with the exception of a meeting like this, I never hear about our scientific diving program. Once a year Michael gives me a report and it seems to me that things are working really well. It is a credit to all of you and the efforts you put into this kind of work collectively that few folks in my position get a phone call in the middle of the night or a visit in the morning to hear an emergency briefing from the diving program, and that really is good news.

The Smithsonian has great venues and places to see above water as well and I invite you to take advantage of this opportunity. I commend you for your work and look forward to seeing this workshop's results. Thanks all for coming and I wish you well for your meeting.

David L. Evans
Smithsonian Institution
Under Secretary for Science

PRESENTATION OF THE ISSUES

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The Ocean Action Plan calls for federal agencies to employ an ecosystem-based approach to studying and managing the marine environment. A majority of the marine ecosystem habitats of interest are located in waters of up to 400 fsw depth, which roughly corresponds to the continental shelf and the photic zone. This workshop will examine the existing technologies with the goal of establishing a robust capability for government agency sponsored (non-military) scientific divers to once again work at depths of up to 300 feet through a phased approach.

Shallow-water coral reefs are well understood, as are the linkages between adjacent mangroves and seagrass beds and their contributions to the reef ecosystem. Akin to limiting a tropical rainforest biologist from climbing higher than 10 m (thereby missing the majority of biodiversity that resides in the canopy), a scientific diver cannot effectively study the biodiversity and contributions of the deep reef to the shallow-reef system, due to technology and training limitations. Our understanding of the reef ecosystem, *in toto*, is therefore vastly impaired.

Scuba diving conducted by scientists is an invaluable research tool; a trained scientific eye under water provides research value and flexibility that unmanned systems often do not. Scripps Institution of Oceanography's first scientific diver was Chinese biologist Cheng Kwai Tseng who in 1944 used Japanese surface-supplied abalone gear to collect algae off San Diego. When Scripps organized its scientific diving program in 1951, the maximum depth certification for open-circuit, compressed air scuba was 250 fsw (based on the U.S. Navy's maximum PO_2 limit of 2.0 atm at the time.) Safety concerns have gradually eroded this depth limit to what has become a 190 fsw operational compressed air window for scientific diving, as published by the Department of Labor (OSHA) in 1982 and 1985 (29 CFR 1910). OSHA does not regulate the scientific diving community with regard to technology, which provides us with the operational flexibility to employ mixed gases (through surface supply and rebreathers) and underwater habitats in our research methodology to meet the Nation's marine science needs.

Reliable commercial diving technology exists to reach these depths, but is not routinely employed by the scientific community. What would it take to train a competent scientific diver in surface-supplied mixed gas diving, where the dive, gas mix, depths, bottom times, voice communication, and decompression are controlled from the surface? Would the limitations of diving on a hose under these constraints outweigh the advantages of immediate access to 300 fsw?

Attempts at introducing rebreathers into mainstream scientific diving programs have met with inertia and significant safety concerns due to issues of reliability, availability, time investment in training, and proficiency requirements. The workshop focus is therefore not on rebreathers *per se*, as they have received much attention through numerous venues over the last 15 years and should continue to evolve on a parallel track. Rather, we will focus on enabling an effective, robust scientific diving capability to conduct research between 190 and 300 fsw by evaluating a re-expansion of the scientific diving envelope through mixed gas and surface-supplied techniques.

It is within the scope of this workshop to address, at a minimum, the following topics:

1. Review of past efforts to expand scientific diving capabilities (*e.g.,* AAUS workshops, Link Symposium, Underwater Intervention, etc.)
2. Comparison of advantages/disadvantages of advanced diving techniques and equipment, including but not limited to safety, training, limitations, cost, and support requirements:
    - Trimix scuba
    - Rebreathers
    - Surface supplied (bell/no bell)
    - Saturation (fixed, mobile)
3. Evaluation of existing commercial diving and military procedures' applicability (fly-away saturation systems, mixed gas surface-supply) as an advanced scientific diving tool;
4. Review advances in decompression protocols that optimize the dive profile decompression obligations; and
5. Through user group input assess advanced scientific diving needs for ecosystem management objectives;

NOAA-NURP's DEEP SCIENTIFIC DIVING NEEDS

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Introduction

I would like to welcome you and thank you for your time and effort on behalf of the National Oceanographic and Atmospheric Administration (NOAA), NOAA's Undersea Research Program (NURP), and the National Marine Sanctuary Program. First, I would like to acknowledge and thank Michel Lang for organizing and conducting what promises to be a very significant workshop. Without his inspiration, enthusiasm, and hard work it would not have happened. Second, Laurie Penland is assisting Michael and she also deserves a round of applause. Finally, I would like to thank the Smithsonian Institution for providing great facilities for this meeting and dinner this evening.

In his opening remarks Michael provided us a clear example of the Smithsonian's need for scientists to wet dive deeper than 190 feet and he also stated the diving technologies this workshop will review as potential methods of safely achieving that goal. I would like to provide a general statement of NOAA's need for deep diving and later in the workshop other NOAA personnel, and NOAA supported researchers, will provide specific examples of their program's deep diving needs.

NOAA's mission is *"to understand and predict changes in Earth's environment and conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs."* The ecosystem goal of NOAA is to "*protect, restore, and manage the use of coastal and ocean resources through an ecosystem approach to management."* The NOAA programs striving to meet these goals include: habitats (deep corals), coastal and marine resources, protected species, fisheries management, aquaculture, enforcement, ecosystem observations and ecosystem research. It is difficult to imagine that NOAA can accumulate the knowledge needed to achieve its mission without scientists thoroughly studying the ocean's ecosystems at water depths deeper than 190 feet.

National Undersea Research Program

NURP's mission is "*to place scientists under the sea to conduct priority research in support of NOAA's goals."* NURP is a national program, composed of a network of regional centers and a national institute. Ninety percent of NURP funding is distributed outside of NOAA through grants and cooperative agreements to underwater scientists who are performing NOAA management priority research. Ecosystem-appropriate underwater technologies applied by NURP include: mid- and deep-water manned submersibles, Autonomous Underwater Vehicles, Remotely Operated Vehicles, open-circuit nitrox and mixed-gas scuba diving, and saturation diving in an undersea laboratory. In spite of the availability of underwater cameras and sampling devices that can be operated from the surface, many scientists prefer wet diving to perform their sampling and underwater manipulations. In fact, NOAA, through the NOAA Dive Program and NURP, sponsors approximately 25,000 dives per year. The vast majority of these dives are to depths less than 130 feet. However, many scientists have expressed the need to dive to 300 feet and beyond.

NURP Support of Advanced Diving

NURP is responsible for ensuring that all NURP-funded undersea research is conducted safely and efficiently in accordance with appropriate standards and procedures. Currently, all NURP-sponsored diving must be done by organizations accredited by either the NOAA Dive Program (NDP) or the American Academy of Underwater Sciences (AAUS). The NDP governs all diving by NOAA employees while the AAUS covers diving at universities and research institutions.

Over the past several years, the NURP centers have received an increasing number of inquiries and proposals to conduct wet diving to depths beyond 130 feet using “advanced” diving equipment and procedures. In keeping with NURP’s responsibility to support “safe” diving operations, NURP began investigating the status of current methodologies to support such efforts. Communications with Dave Dinsmore, NDP Director, and several members of the NURP dive council, who are also diving safety officers with AAUS member institutions, revealed that both the NDP and the AAUS were developing extended-range diving programs. This information was very encouraging and NURP agreed to provide assistance to both of these organizations to help foster continued development of deep diving programs and to encourage standardization of procedures for reciprocity.

Based on this investigation in early 2003, NURP established the goal of providing scientific divers access to 300-foot depths. Three priority elements were identified: institutionalize deep open-circuit, mixed-gas diving within NURP, work with the NDP and the AAUS to introduce the use of closed-circuit mixed-gas rebreathers, and support deep diving consortiums.

To date, NURP/UNCW has finalized its deep open-circuit mixed-gas diving manual and made it available to other centers. NURP worked with Dave Dinsmore, NDP Director, to establish a closed-circuit mixed-gas rebreather safety standard and the deep diving consortium at the University of Hawaii is moving forward.

The NURP Diving Council members reviewed all drafts of the rebreather standard and participated in the drafting or approval of the new AAUS procedures. I would like to recognize the efforts of the current NURP diving council members: Jeff Godfrey, Rose Petrecca, Lance Horn, Doug Kesling, John Marr, Marc Slattery, Terry Kerby, and Brenda Konar. Five of the council are participating in this workshop and will be heard from later in the program.

NOAA-Supported Advanced Diving Events

From 1982-1985, NURP/UNCW supported surface-supplied diving. In 1986, the program was discontinued for several reasons: inadequacies of the support vessel, limitations of technology, and the lack of interested/qualified personnel. In 1993, AAUS standards included mixed gas and in-water decompression, allowing diving below 190 feet. The U.S.S. MONITOR project involved UNCW open-circuit dives to 235 feet, and from 1998-2002, U.S. Navy surface-supplied, bell- and saturation-diving techniques. In 2005, the NOAA Diving Program adopted a rebreather standard and the AAUS approved rebreather operational standards.

How did we get to where we are today, and what will this workshop do for us?

The current workshop is building on past collaborative efforts among scientific, commercial, and military diving organizations to promote safe practices in scientific deep diving including:

- **A 1999 AAUS Workshop on the Feasibility of Technical Diving for Science.** This workshop on Catalina Island concluded that technical diving was here to stay, scientific diving below 130 feet could benefit from some improved techniques, no standards existed for using technical diving procedures, and new AAUS standards were in need of development.

- **The 2002 Link Symposium on Sea and Space.** The overarching recommendations from the Link Symposium at Kennedy Space Center included action on the following concepts: a family of habitats to support wet diving to 650 feet, development and refinement of rebreather technologies, and improved communication between commercial, scientific, and U.S. Navy diving programs, specifically including a session at the 2003 Underwater Intervention Symposium.

- **The 2003 Underwater Intervention Symposium.** In response to the Link symposium recommendations an expert panel on “Advancements in Wet Diving for Science” was convened in New Orleans, consisting of representatives from NOAA, Smithsonian Institution, commercial diving, U.S. Navy, and academia. NURP announced a 300-foot Advanced Diving Program, and with the NOAA Diving Program, agreed to prioritize the development of a rebreather equipment safety standard. One conclusion was that a future meeting should directly address how the scientific community could use the commercial and military systems.

2006 Advanced Scientific Diving Workshop Objectives

This workshop provides us the opportunity to produce recommendations for civilian scientific diving to 300 feet using open-circuit scuba, closed-circuit rebreathers, surface-supplied, bell-, and saturation diving, including the use of U.S. Navy and commercial diving facilities. I see the result of this process as a roadmap, and just as there is more than one route between most cities, there is more than one method that will allow scientists to dive safely to deeper depths. What this workshop can do is point out where we can proceed quickly down a smooth roadway and where we need to slow down to negotiate deep potholes and other potential hazards.

HISTORIC PERSPECTIVE: SCIENTIFIC DEEP DIVING AND THE MANAGEMENT OF THE RISK

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Introduction

Science is the study of the physical world and its manifestations, especially by using systematic observation and experiment. The effective pursuit of science is dependant upon the ability to use state-of-the-art technology and training in order to expand the envelope of scientific knowledge in the area under investigation. Historically, each stage of scientific diving development has resulted in the parallel development of improved life-support systems and research tools that have enabled safe underwater work environments. Diving is but one of the countless tools that is used in science. The inability to utilize optimal technology creates a stifling environment in science as well as scientific diving.

It is clear that mankind has been studying and working in the underwater environment for several thousand years. The results of these efforts, although primitive, have benefited the development of life on earth as we know it. Although few early records exist, evidence that the study of the underwater world has steadily evolved is undeniable. The following limited timeline represents an effort to follow the development of diving technology as it relates to scientific endeavor.

Timeline

332BC: Aristotle described the diving bell that Alexander the Great was to have used for underwater observations in the Mediterranean. Reports that he was using underwater swimmers for military purposes also seem credible.
1500's: Da Vinci recorded evidence that the study of underwater life support was moving forward and presented a conceptual scuba apparatus.
1535: Lorena developed a true diving bell.
1650: Von Gierke was credited with the first effective air pump.
1691: Halley's Bell with primitive air supply system.
1715: Lethbridge's Diving Engine, 30 minutes at 60 ffw.
1774: Freminet performed surface-supplied dives at 50 ft.
1827: Pouillet piston-controlled, pneumatic regulator.
1828: Deane Brothers marketed a helmet and diving suit.
1837: Siebe connected the helmet to diving suit.

1850: Green used diving armor in Lake Erie for salvage between 15-70 ffw. Green dived 158 fsw on Silver Banks, many dives were reported over 140 fsw.

1865: Rouquayrol-Denayrouse Aerophore permitted diver to disconnect surface-supplied air and move about freely for a short time using a reservoir of compressed air. 150 fsw limitation.

1876: Fleuss developed a self-contained compressed O_2 unit.

1880: Fleuss device used by Lambert 60 ft down and 1000 ft back in a flooded tunnel.

1882: U.S. Navy Diving School, Newport, Rhode Island.

1893: Bouton made first underwater photographs.
Dahl quantitatively assessed benthic community.

1904: British working dives to 210 ft.

1905: Manual for Divers, U.S. Navy Diving School trained to 200 ft.

1906: Haldane diving tables, 204 ft on air.

1908: Haldane reported on the prevention of compressed-air illness.

1913: Williamson made underwater motion picture, later he filmed 20,000 Leagues Under the Sea, a classic.

1914: U.S. Navy 274 fsw working air dives from U.S.S. Walke.

1915: U.S. Navy 304 fsw working air dives. Recovery of U.S.S. F4 submarine.

1917: U.S. Navy MkV diving system on line.

1918: Ohgushi Peerless Respirator developed in Japan – self-contained air dives of 282 to 324 fsw were successful. A type of “bite valve” permitted “demand” air delivery to the diver’s mouth.

1920: Le Prieur developed self-contained apparatus.
U.S. Navy researched heliox for deep dives.

1925: Diving experiments Helium/Oxygen 80/20 .

1927: U.S. Navy Experimental Diving Unit developed HeO_2 capabilities.
Florida Geological Survey used hard hat.

1933: Corlieu patent for swim fins.
Le Prieur used 1500 psi air with manual valve and no regulator.

1934: Kitching used helmet for kelp bed observations.

1935: Behnke studied O_2 toxicity effects at PO_2 of 1-4 ata. Determined that bottom time, depth, and highly variable individual response were critical. “Oxygen Window”.

1937: Behnke at NEDU did 500’ chamber dives on HeO_2 .
Nohl worked with Dr. End to 420 ffw in Lake Michigan using HeO_2.

1939: U.S.S. Squalus dives used air and heliox to 243 fsw, recovered submarine.

1942: Cousteau/Gagnan redesigned a pressure regulator for use underwater.

1944: Scientific diving at Scripps Institution of Oceanography by Chinese biologist Cheng Kwai Tseng using Japanese surface-supplied abalone gear to collect algae.

1945: Zetterstrom reached 528 ft on hydrogen/oxygen but died from an acute lack of oxygen on ascent, unable to change over his gas supply from the deep mix.

1946: The Aqualung was commercially marketed.

1947: Haymaker at Scripps used hardhat gear in Scripps Canyon.
Dumas used Cousteau/Gagnan regulator to dive to 307 fsw.

1948: 10 Aqualung units became available at Rene's Sporting Goods in Westwood California. Post in NYC and Pederson in Chicago were also selling Aqualungs.
HMS Reclaim divers set a series of records on HeO_2 - final 540 ft depth.
1949: Limbaugh and Rechnitzer used Aqualungs for scientific diving at UCLA.
1950: Limbaugh and Rechnitzer moved to Scripps. Limbaugh became chief diver.
1951: First official diving course at UCLA, Scripps Institution campus.
Skin Diver Magazine began publication.
1953: Bradner from University of California developed first wet suit.
Popular Science Magazine published information on a "build your own" scuba.
1954: Los Angeles County Underwater Program followed Scripps training course. The L.A. County dive manual prepared by Bev Morgan had air tables to 300 ft.
Scripps Institution dive program listed 4 divers certified to 250 ft among 60+ divers.
1955: First L.A. County Underwater Instructors Course.
1956: Royal Navy used heliox to dive to 600 ft.
U.S. Navy Experimental Diving Unit published Standard Decompression Tables.
300 ft certifications at U.S. Naval School – Deep Sea Divers, Washington, D.C.
1957: Sea Hunt TV series began.
1958: U.S. Navy published Dive Tables for air down to 300 fsw.
Keller developed 400 tables for variable mix HeO_2 dives to 1312 ft, he also performed a chamber dive to 1000 ft using a Calypso single-hose regulator.
1959: YMCA Scuba Program developed 1st National Diver Certification program.
1960: National Association of Underwater Instructors formed.
1961: Sea Lab 1 – 192 ft.
Keller and MacLeish dived 725 ffw using Keller's mixes with 30 min. O_2 stop at 50 ft.
1962: Conshelf One used 2 divers at 33 ft for 7 days.
Link experimental heliox dive to 200 ft for 24 hours.
1963: U.S. Navy 300 fsw Extreme Exposure Tables for air.
1964: U.S. Navy Sealab I, four divers 11 days at 193 ft.
U.S. Navy MK VI semi-closed circuit unit with 300 ft capability.
1965: U.S. Navy Sealab II revolving crews every 15 days at 205 ft, Carpenter for 30 days.
1966: PADI formed.
1967: Undersea Medical Society founded.
H. Watts dived 390 ft on air.
1968: Gruener and Watson dived to 437 ft on air.
U.S. Navy saturation to 825 ft with excursions to 1025 ft.
1969: Sealab III at 600 ft. Program suffered as a result of a fatality.
1970: Deep Diving System MK1 open sea dives to 850 ft.
1972: Deep Diving System MK2 open sea dives to 1010 ft.
1973: U.S. Navy PO_2 of 1.6 atm for normal use 30 min. Emergency use 2.0 atm for 30 min.
1975: Deep Diving System MK1 open sea dives to 1148 ft.

1976: OSHA enacted proposed rulemaking covering commercial diving operations. AAUS formed to provide representation for scientific diving.
U.S. Navy light-weight mixed-gas diving gear used for 300 ft dives on heliox with Superlite 17 and Kirby-Morgan Band Mask.
1977: Final standard for commercial diving enacted that included scientific diving.
U.S. Coast Guard commercial regulations excluded educational/scientific diving.
1979: U.S. Navy divers performed 37 day, 1800 ft chamber dive .
1980: U.S. Navy MK XII replaced MK V diving system.
1981: Manned chamber dive at Duke University to 2250 ft.
1982: OSHA provided scientific diving with exemption from commercial regulations.
1983: First commercially viable electronic dive computer, the EDGE, was marketed.
1985: OSHA Guidelines for Scientific Diving – 1910 Subpart T App B.
U.S. Navy MK12 diving system approved for fleet use.
1988: Comex saturation dive to 1706 ft with excursions to 1742 ft.
Exley worked at 780 ft on trimix gas in Mexican cave.
1989: Exley dived to 881 ft on trimix gas in same cave.
1990: Gilliam to 452 ft on air. (claimed 2000+ dives over 300 ft since 1958).
NOAA PO_2 at 1.6 atm normal use 45 min., emergency 120 min. or 2 atm for 30 min.
1993: U.S. Navy had PO_2 of 1.3 atm with unlimited exposure. MK21 Superlite replaces MK XII system.
Gilliam recorded a dive to 475 ft on air.
1994: Manion credited with 500 fsw on air (computers recorded 490 ft and 509 ft).
Bowden reaches 925 ft on mixed gas, Exley fails to surface, later recovered.
1997: Richard Pyle made a series of 12 ~300 ft closed-circuit dives at twilight zone .
1999: British depth record holder Andrews dived on air to 513 ft.
S. Watts dived to 425 ft on air in Cozumel.
2001: NOAA Dive Manual listed PO_2 at 1.6 atm for 45 min., PO_2 at .6 no limit.
Howard Hall filmed *Coral Reef Adventure* at depth, many dives in the 325-400 ft range.
179 day project. Pyle makes 400 ft dive.
2002: 5-dive series on U.S.S. Tahoe at 400 ft on trimix. New Millenium project.
2003: Ellyat open-circuit dived to 1027 ft.
2004: Bushmans cave - closed circuit diver Shaw found body at 886 ft.
Bennett to 1010 ft.
2005: Gomes open-circuit dived to 1044 ft, also had 927 ft dive on record.
Shirley closed-circuit dived to 927 ft.
2006: 1,160,000 hits on the internet for "technical dives 400 ft ".
"Scientific divers and deep diving" had 2,180,000 hits.
"Scientific deep diving human" had 1,850,000 hits.

This timeline is based upon literature cited in the references. Some data is recognized to be autobiographical with its attendant risks for interpretation. Setting aside concerns for "records," it becomes obvious that maintaining arbitrary depth limits in the presence of a rapidly expanding knowledge and technology database is clearly shortsighted. The ability to develop and use state of the art technology is fundamental to the evolution of scientific diving and is only limited by our own community standards.

Life support capabilities have evolved and an amazing number of diving projects are using the newer technologies to explore and study deep reef systems, deep cave systems, underwater movie locations and deep wrecks. These projects, of which there are hundreds, involve groups of dedicated scientific divers adding new knowledge in many different areas of study. It does not take great investigative skill to recognize that most of these deep diving projects are being conducted outside of the OSHA "narrow exemption" limits. It is frustrating to consider that "AAUS scientific diving" effectiveness may be underdeveloped as the result of arbitrary and unnecessary restrictions.

It has now been almost 30 years since the OSHA challenge to regulate scientific diving. The scientific diving community has continued to mature and the AAUS role has expanded in its efforts to meet the challenges in the areas of underwater research and education. It appears to be time to review the parameters of scientific diving in order to encourage the use of more advanced technology for conducting the scientific studies that involve the quest for knowledge.

Following the timeline it appears that the following statements are reasonable:

1. The concept of a 190 ft limit for air diving may be overly conservative.
    a. Divers were working effectively on air since the early 1900's.
    b. By 1914, air was being used regularly to 300 ft.
    c. The Ohgushi self-contained apparatus was used at 324 ft in 1918.
    d. Air decompression tables have been widely used to 300 ft.
    e. Surface-supplied air dives to 300 ft are not uncommon.
2. Using mixed-gas combinations are no longer a great risk.
    a. Mixed-gas technology has been used since the 1900's.
    b. Mixed gas is currently being used at depths on the order of 1000 ft.
    c. Light-weight, mixed-gas apparatus has been used successfully for over 30 years.
3. Scientific diving has been somewhat slow in taking advantage of advancing technology.
    a. Scientific diving has not moved to the forefront of technology.
    b. Regulatory pressure stifles creative advancement of technology.
    c. Commercial and military advances are rarely available to scientists.

Scientific Diving Regulations

Regulations (Standards - 29 CFR)
Guidelines for scientific diving - 1910 Subpart T App B

Regulations (Standards - 29 CFR) - Table of Contents

• Part Number:	1910
• Part Title:	Occupational Safety and Health Standards
• Subpart:	T

- Subpart Title: Commercial Diving Operations
- Standard Number: 1910 Subpart T App B
- Title: Guidelines for scientific diving

This appendix contains guidelines that will be used in conjunction with 1910.401(a)(2)(iv) to determine those scientific diving programs which are exempt from the requirements for commercial diving. The guidelines are as follows:

1. The Diving Control Board consists of a majority of active scientific divers and has autonomous and absolute authority over the scientific diving program's operations.

2. The purpose of the project using scientific diving is the advancement of science; therefore, information and data resulting from the project are non-proprietary.

3. The tasks of a scientific diver are those of an observer and data gatherer. Construction and trouble-shooting tasks traditionally associated with commercial diving are not included within scientific diving.

4. Scientific divers, based on the nature of their activities, must use scientific expertise in studying the underwater environment and, therefore, are scientists or scientists in training.

[50 FR 1050, Jan. 9, 1985]

A 01.26.06 review of the current OSHA 29CFR1910.401 reveals the following:

- 1910.401(a)2 …However this standard does not apply to any diving operation:
- 1910.401(a)(2)(iv) Defined as scientific diving and which is under the direction and control of a diving program containing at least the following elements:
- 1910.401(a)(2)(iv)A. Diving safety manual which includes at a minimum: Procedures covering all diving operations specific to the program; procedures for emergency care, including recompression and evacuation; and criteria for diver training and certification.
- 1910.401(a)(2)(iv)B. Diving control (safety) board, with the majority of its members being active divers, which shall at a minimum have the authority to: Approve and monitor diving projects; review and revise the diving safety manual; assure compliance with the manual; certify the depths to which the diver has been trained; take disciplinary action for unsafe practices; and, assure adherence to the buddy system (a diver is accompanied by and is in continuous contact with another diver in the water) for scuba diving.

It is ominously clear that the language in the exemption is vague and ambiguous, which means that "what we understand may not be what they said". The importance of maintaining our exceptional safety record and training standards while making progressive positive changes in our operations cannot be overstated. Careful attention to balancing risk against benefit is a necessity.

Risk Management

The issue of risk versus benefit has been an integral part of diving technology and research since the beginning of the evolution of diving itself. Traditional scientific diving operations have been slow to change in the face of new developments and controversy has followed virtually every new development. A few of the more memorable issues have centered around single versus two-hose regulators, life vests versus buoyancy compensators, alternate air sources, dive tables versus dive computers, and then there is this year's crop of Rec versus Tek, air versus mixed gas, risk versus records, deep dive first, etc. Unfortunately, the controversies have generally been based upon traditional points of view and emotion rather than upon credible scientific fact. I find a quote by Ben Franklin to provide some perspective to this issue. In the year 1887, he observed "Having lived long I have experienced many instances of being obliged by better information and for consideration to change opinions even on important subjects which I once thought right but found to be otherwise."

It appears that we may be in a similar quandary with the focus of this workshop. There appears to be a traditional and now long-standing position that diving beyond 130 ft carries an unacceptable degree of risk for the diver. The question of the risk versus benefit of deeper dives has not, to this date, been provided with a satisfactory answer based upon valid scientific evidence. It is well known that the 130 ft, or for that matter the 190 ft "maximum depths," are routinely ignored by mission-oriented divers. In spite of this, there is the well known fact that many divers will dive their computers with little concern about depth and, if the practitioners are to be believed, with no symptoms of decompression illness or other negative effects. If the risk is minimal, then the question, "what are the benefits and are they sufficiently important to warrant the risk?" becomes paramount.

All too often we have been placed in the intellectually awkward position identified by Poul Anderson who stated "I have never encountered a problem, however complicated, which, when viewed in the proper perspective, did not become more complicated." If we are to evaluate the risks of increasing science diving capability then it appears that we must delve into the complications that go with the understanding of the problem in order to properly assess any risk involved.

It is perhaps worthwhile to spend a few moments on the issue of risk assessment in diving. One of the first problems we face is identifying the nature of the risk and determine whether it is acceptable to our diving population. We know that diving has a number of inherent risks associated with it. By and large, they are acceptable to the diving population even though litigators for personal injury are quick to point out that the risks were not clearly defined to their clients who were, therefore, uninformed about the true nature of the risk prior to their injury.

It appears that risk assessment on this issue must look both forward and backward in order to develop a data base for rational assessment. We have elements of the diving population who have amassed a large amount of deeper diving experience. We have elements of the diving population who are adamantly opposed to dives over 130'. We have tables and computers that give some dive time advantages when compared one to the other. While we may never gain a complete understanding of the problems, there are some tools available for increasing our understanding.

Friedman, in an internet paper on "Understanding Risk", identifies four well-accepted analysis steps needed for the assessment of risk. They are identifying the hazards, establishing the relationship between a dose and the response to that dose, analyzing potential public exposure, and describing the risk. Using his categories and taking the blame for any misinterpretation of his points leads to the following conclusions.

1. The identification of hazards should be based upon existing scientific evidence, which can show a cause and effect relationship between making dives somewhat beyond currently accepted limits and serious injury to the diver.
2. The dose/response relationship would require that an objective decision be made as to the degree to which differential pressures of the contents in the breathing gases cause an observed effect. This would normally involve a study of a population of divers and its known response to various dive profiles. We need to know the likelihood of increased injury in the diving population that is produced by the hazard. The length of the exposures, surface intervals, and the depth profiles are all part of the "dose" that must be evaluated. Some will say that this has already been done and is in the literature. The literature also contains information about divers who continually push the limits without serious consequences. Risk is relative to a specific set of conditions.
3. The analysis of potential public exposure will depend, in part, on the potential damage or benefits of the practice of diving deeper profiles. It may also depend upon the effect of a variety of intervening variables such as physiologic fitness, age, fluid balance, comfort level, sensitivity to internal change, psychological variables, work rate, temperature and many others which may have an effect on decompression effectiveness. What is the specific nature of the calculated risk that divers must accept if they choose to go deeper?
4. The description of the risk is then based upon the objective evaluation of the likelihood of the occurrence of undesirable side effects following a given "dose" of deeper exposure. We will never be without risk in diving but we must use reasonable care in determining the degree of risk we are prepared to accept. Usually, risks of 1 in 1,000,000 are considered acceptable for virtually any risk. Risks at the level of 1 in 100,000 are minimal but the severity of the injury becomes an issue. Brylske identifies 1,000,000 scuba divers with 935 reported injuries for 1996. That appears to be 1 injury for every 1,070 divers, but when compared to swimming, which has an injury for every 634 swimmers, scuba diving is relatively safe. The level of risk associated with diving in general has always been quite well accepted by the diving population. Unfortunately, such assessment needs a review of the actual number of exposures or the accurate size of the population as well as the number and severity of the injuries to make a reasonable assignment of risk. Without the denominator the attempts at assigning risk are speculative.

A further problem seems to arise when attempting to establish the level of informed consent that would be needed for the individual to adequately evaluate the risk of a given exposure. How much knowledge about the risk is enough to develop a reasonable and prudent basis for acceptance of a given level of risk? When does the risk become unacceptable? The realistic assessment of risk must rely on an examination of data drawn from the various disciplines that study the various aspects of the problem. Whoever said that there is no such thing as a simple problem had the right idea. It is critical that we do not develop a "jump on the bandwagon" mentality that obscures the nature of the calculated risk and avoids the serious consideration of the potential consequences of the practice of extending a given depth limit. Developing "rules" without sufficient data may well have been an important factor in the development of our current dilemma. It will be important to be able to establish that based upon the evidence, the risk while diving beyond 190 ft is either greater, less than, or the same as the traditional depth limits of 130 ft or 190 ft (neither of which were considered a problem historically).

At any rate, the communication of the best information available to the widest membership in the diving community is clearly in the best interest of the safety of divers. This information must be accompanied by the recognition that there can be no guarantee of ultimate safety and that all risks are relative to the specific conditions of each dive. Diving does and always has involved a calculated risk that the diver needs to assess for every dive that is made. All concerned must make personal decisions regarding the degree of relative risk that is acceptable to them.

Conclusion

A substantial search of literature and conversations with knowledgeable resource persons has not revealed any objective evidence, scientific or otherwise, that provides for definitive acceptance or prohibition of dives beyond 190 ft. It appears that a careful analysis of the risk/benefit issues is long overdue.

The 1956 U.S. Navy Manual on Submarine Medicine Practice had Navy Standard Decompression Tables to 300 ft. These were not exceptional exposure tables, divers were trained to 300 ft.

The 1959 version of the U.S. Navy Dive Manual gave the following cause for decompression sickness: "Decompression sickness is caused by inadequate decompression following a dive, but does not necessarily mean that the decompression table has not been followed properly. An excessive amount of gas in the tissues can result from any condition (in the man or in the surroundings) that causes an unexpectedly large amount of inert gas to be taken up at depth or that results in an abnormally slow elimination of gas during the decompression procedure. In such situations, following the table to the letter would not always assure adequate decompression. However, the decompression tables are designed to cover all but exceptional cases of this sort, so the actual risk of decompression sickness is small if the right table is properly employed."

The question could be raised as to which is the “right” table.

The development of the current position appears to be evolutionary in the sense that the logic of the position has grown from well accepted roots in the diving industry. If data is developed from these records that reinforces the changes, the changes are probably a good thing. If, on the other hand, changes are accepted because they “make good sense” and then become the “party line” without any reasonable data, then we may find ourselves unnecessarily restricting our diving behavior.

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DECOMPRESSION SICKNESS AND OXYGEN TOXICITY IN U.S. NAVY SURFACE-SUPPLIED HE-O_2 DIVING

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Introduction

The scientific diving community has identified a need to work safely and cost effectively at open-water depths up to 300 fsw. Careful consideration of the risks associated with such diving – and the costs of measures to mitigate them - is required to select optimal strategies for meeting this need. Some of this consideration has already been completed, resulting in our focus at this Workshop on surface-supplied helium-oxygen (He-O_2) diving. A variety of environmental/physiological hazards govern the types of equipment and procedures – and the associated logistical complexity – required to conduct this type of diving. Principal among these are inert gas narcosis, which motivates use of helium as the inert gas diluent in diver breathing gases, and decompression sickness (DCS), which is avoided by staged decompression and aggressive exploitation of the physiological oxygen window. Increased exploitation of the oxygen window to reduce DCS risks or decompression times engenders another principal hazard; that of central nervous system (CNS) oxygen toxicity (Tikuisis and Gerth, 2003). A brief review of the history of how the risks of DCS and CNS oxygen toxicity have manifest and been managed in U.S. Navy surface-supplied He-O_2 diving from 1970 to present illustrates issues that may have to be faced by the scientific diving community as it undertakes similar diving operations.

U.S. Navy Diving Manual (Mar-1970)

New Oxygen Partial Pressure Tables for Helium-Oxygen Decompression were published in the March-1970 issue of the U.S. Navy Diving Manual. In the ensuing 14 years, 185 man-dives on these tables to depths of 200 fsw or greater with bottom times of 30 min or more were reported to the Navy Safety Center. These reports indicated that twenty DCS cases occurred in this relatively small number of dives.

U.S. Navy Diving Manual Revision 3 (15-May-1991) and Revision 4 (20-Jan-1999)

The unacceptably high 11% incidence of DCS (20/185) that accompanied use of the 1970 Helium-Oxygen Decompression Tables was addressed with extensive revisions of the tables for the 1991 issue of Revision 3 of the Diving Manual. Measures taken to decrease the DCS risks of schedules in the revised tables included:

- Tables were converted from O_2 partial pressure format to the depth-time format of the Standard Air Decompression tables. In the course of the conversions, schedules were computed with minimum PO_2 (maximum P_{He}) at each depth. Values 2% lower than operationally allowed were used to compute schedules for dives to depths of 300 fsw or less:
    - 14% O_2 used for dives to depths ≤200 fsw (operational minimum: 16% O_2)
    - 10% O_2 used for dives to depths >200 fsw (operational minima: 12% O_2 for dives to depths of 210–300 fsw; 10% for exceptional exposure dives to depths > 300 fsw)

      This caused dives to be jumped to more conservative schedules when dived within operational limits.
- Added gas switch to 40% O_2 at 100 fsw during ascent in dives to depths deeper than 200 fsw. (Switch to 100% O_2 at 50 fsw during ascent retained)

Other revisions included:

- Ascent rate between stops reduced from 60 to 30 fsw/min
- Reduced bottom PO_2 limit from 1.6 to 1.3 atm

The 1991 Revision 3 He-O_2 Decompression Tables appeared unchanged in the January 1999 issue of the U. S. Navy Diving Manual, Revision 4. As in the 14-year period after issue of the 1970 He-O_2 Decompression Tables, only a relatively small number of surface-supplied He-O_2 dives was completed by Navy divers after issue of the 1991 tables. From 1995 to 1999, 405 surface-supplied He-O_2 man-dives on the tables were reported to the Navy Safety Center. The numbers of dives in each year using the in-water or surface decompression on oxygen (sur-D-O_2) procedures are given in Table 1 (Flynn, 1999).

Table 1. Surface-supplied He-O_2 dives completed 1995 – 1999 by year and decompression model.

Decompression	Year					Total
	1995	1996	1997	1998	1999	
In-water	19	32	21	166	0	238
sur-D-O_2	4	22	7	70	64	167
Total	23	54	28	236	64	405

At least as reported to the Safety Center, the dives were also limited in maximum depth, as shown in Table 2 (Flynn, 1999). Only eight man-dives to depths greater than 250 fsw were reported.

Table 2. Surface-supplied He-O_2 dives completed 1995 – 1999 by schedule and bottom time.

Bottom Time (min)	Schedule Depth Group (fsw)					
	60	70-100	110-150	160-200	210-250	260-300
10	28	10	31(1)	6	21(2)	0
20	8	22	18(3)	10(6)	7	2
30	0	2	7	8	112*	6
40	6	0	0	57(5)	44(4)	0

* DCS. Note: Numbers in parentheses indicate 6 cases of CNS O_2 toxicity in order of occurrence

While only a single case of DCS occurred in these dives, six cases of CNS O_2 toxicity occurred. In five of these cases, symptoms proceeded to convulsions, either in the water or immediately on surfacing.

U.S. Navy Diving Manual Revision 4, Change A (1-March-2001)

The incidence and severity of in-water O_2 toxicity events with the 1991 He-O_2 tables was reviewed at a July 1999 meeting in Groton, CT, where it was concluded that the 1991 tables required revision to minimize future risks of such events. At this point, new quantitative analytic tools were in hand to help ensure that prospective revisions would be accompanied by only minimal increases in DCS risk. The first of these was a linear-exponential multi-gas (LEM) probabilistic model of DCS incidence and time of occurrence that had been calibrated about a composite data set of 4669 He-O_2 and N_2-O_2 man-dives. This model, LEMhe8n25, fully described in a later publication (Gerth and Johnson, 2002), allowed estimation of the DCS risks of schedules in the original 1991 He-O_2 Decompression Tables (Figure 1), and assessment of the impact on DCS risk of any prospective changes to these schedules. A probabilistic auto-catalytic model of CNS O_2 toxicity (Harabin *et al,* 1995) was also available for similar analysis of CNS O_2 toxicity risks in original and revised schedules.

All analyses were completed with bottom mix gas at the maximum oxygen fraction allowed in the original Revisions 3 and 4 He-O_2 Decompression Tables. Dives to depths of 250 fsw or greater included initial descent to 20 fsw on air followed by a 10 minute stop at this depth for gas switch to bottom mix. Chamber time in sur-D-O_2 procedures included a 5-minute air-breathing break after every 30 min of O_2 breathing, except after the last O_2-breathing period before surfacing.

After consideration of a variety of candidate modifications, a final table set with the following modifications, designated Change A, was selected:

- Shifts to 60% He/40% O_2 at 100 fsw during ascent from dives deeper than 200 fsw were removed
- Shifts to 50% He/50% O_2 at 90 fsw or at the first stop shallower than 90 fsw during ascent were added
- Shifts to 100% O_2 at 50 fsw during ascent were removed; Diver remains on 50/50 He/O_2 to completion of any 40 fsw stop
- 50 fsw stop time shorter than preceding 60 fsw stop time in any schedule was adjusted to equal the 60 fsw stop time. The 40 fsw stop time was then set equal to the new 50 fsw stop time.
- In-water decompression stops at 30 and 20 fsw on 100% O_2 were added with stop times determined as follows:
  - 30 fsw stop time = 3 min + 1/3 of original 40 fsw stop time rounded to next least integer;

- 20 fsw stop time = 2/3 of original 40 fsw stop time rounded to next larger integer.

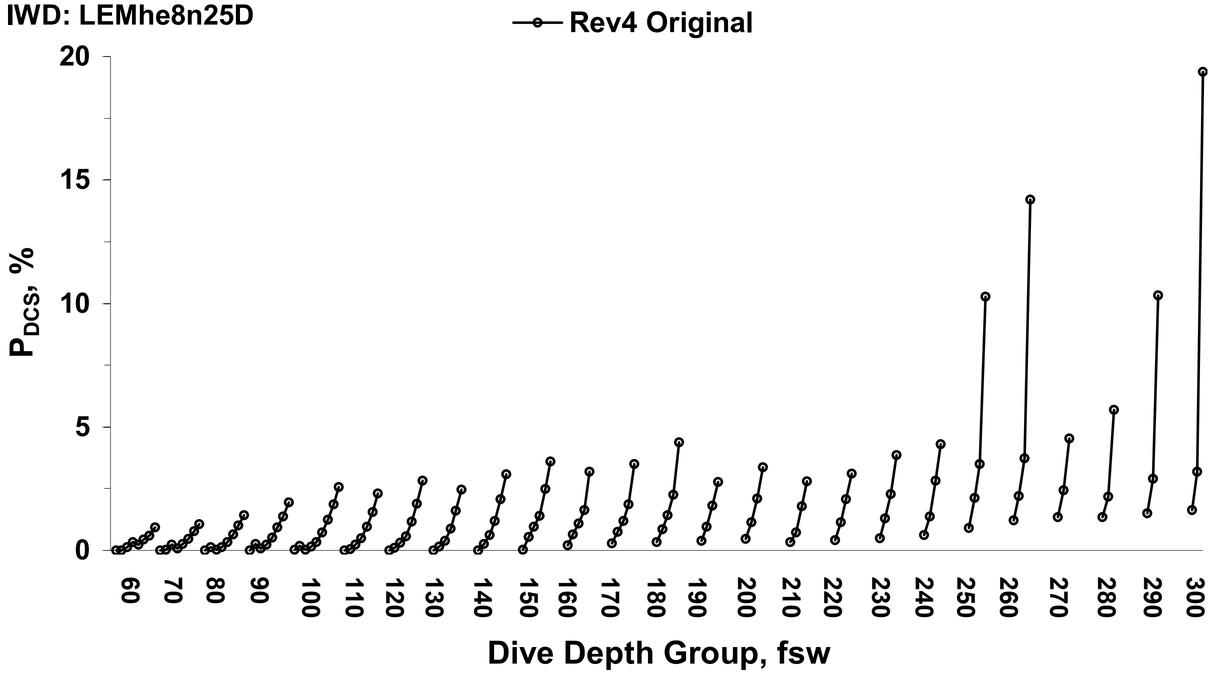

Figure 1. LEMhe8n25-estimated DCS risks of surface-supplied He-O_2 in-water decompression schedules in U.S. Navy Diving Manual, Revision 4 (identical to those in U.S. Navy Diving Manual, Revision 3). Each point indicates the risk for one schedule with schedules arranged in order of increasing bottom time in each dive depth group, and with dive depth groups arranged in order of increasing depth from 60 fsw to 300 fsw. Points within each dive depth group are connected with straight lines to help visually resolve the different groups. The last point at the right of the figure indicates the DCS risk of a 300 fsw, 30 min bottom time dive. Estimated DCS risks for exceptional exposures to depths greater than 300 fsw, or for longer bottom times in each dive depth group, are not shown.

The impacts of these modifications on measures of pulmonary (Harabin *et al*, 1987) and CNS O_2 toxicity are illustrated in Figures 2 and 3, respectively.

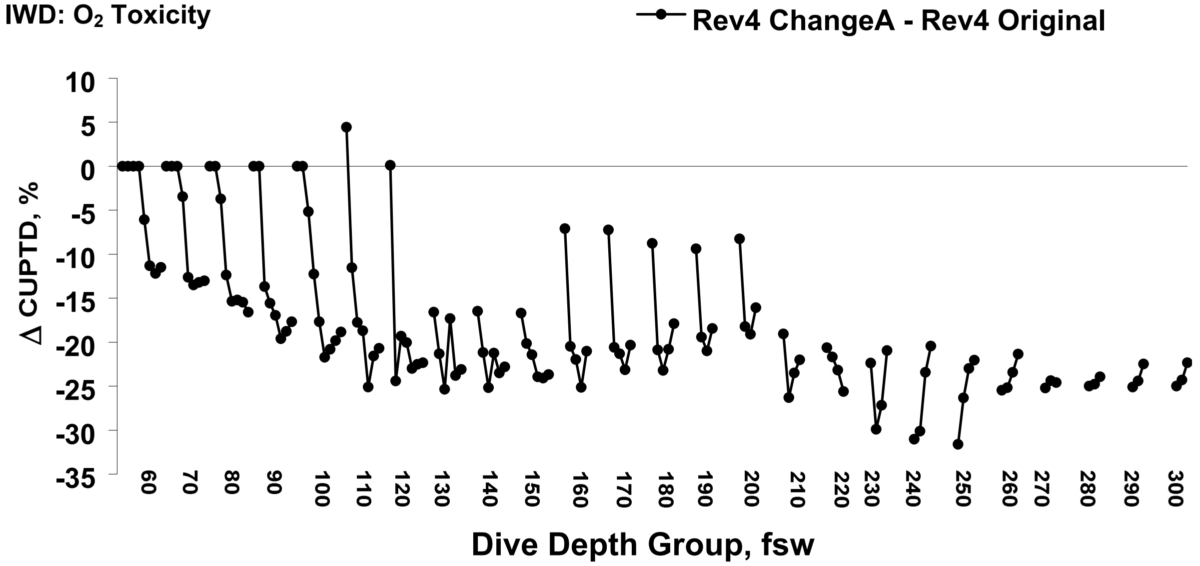

Figure 2. Changes in cumulative unit pulmonary toxic dose (CUPTD) (Harabin *et al*, 1987) caused by modifications designed to reduce risks of in-water CNS O_2 toxicity in 1999 Revision 4 surface-supplied He-O_2 in-water decompression tables.

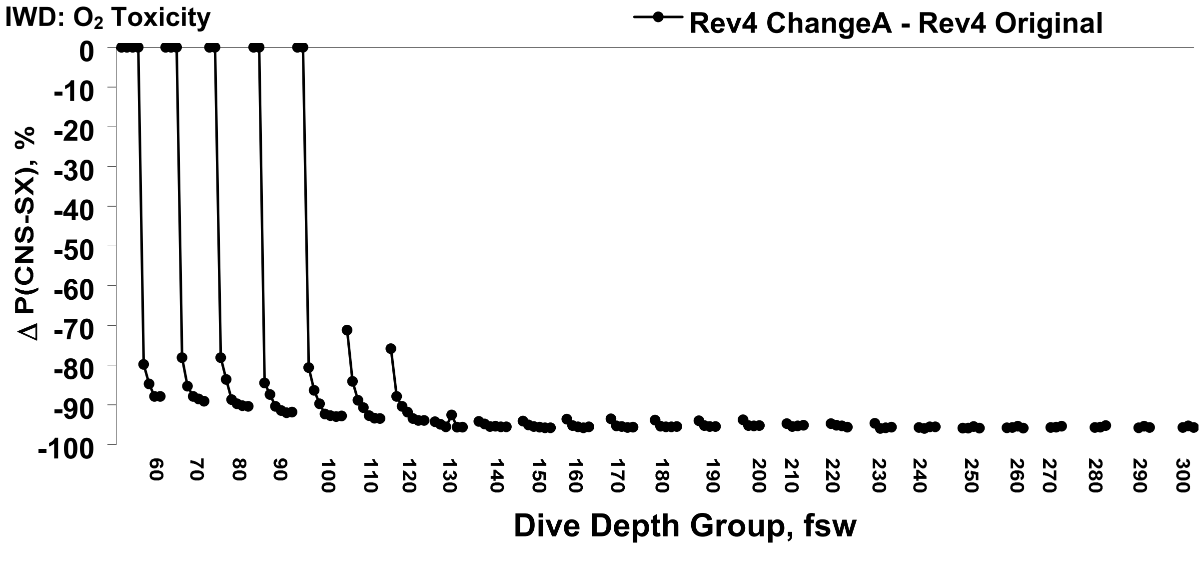

Figure 3. Decreases in estimated overall risks of seizure caused by modifications designed to reduce risks of in-water CNS O_2 toxicity in 1999 Revision 4 surface-supplied He-O_2 in-water decompression tables.

As shown in Figure 4, the generally decreased risks of O_2 toxicity associated with the modified procedures were purchased with only small increases in estimated DCS risk, except for dives with the longest bottom times to depths of 250 fsw or more.

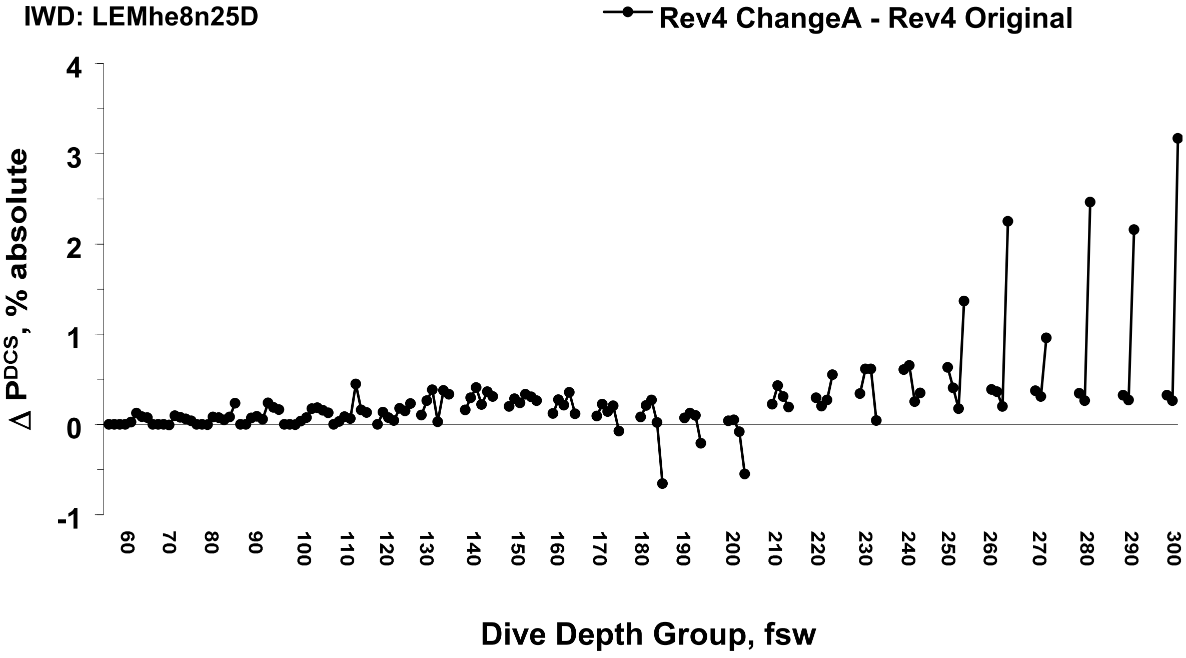

Figure 4. LEMhe8n25-estimated DCS risk changes caused by modifications designed to reduce risks of in-water CNS O_2 toxicity in 1999 Revision 4 surface-supplied He-O_2 in-water decompression tables.

Surface Decompression on Oxygen (sur-D-O_2)

The modifications to the in-water decompression procedures also affected in-water portions of decompressions ended with sur-D-O_2. LEMhe8n25-estimated DCS risks of the sur-D-O_2 schedules without the modifications are shown in Figure 5. The schedules for longer deeper dives within operational limits are seen to have substantial estimated DCS risks. Specific modifications to the chamber time requirements for sur-D-O_2 were consequently made to reduce these risks and mitigate adverse impacts of the in-water changes when the sur-D-O_2 option is exercised. These changes included:

- Split first chamber O_2-breathing period at 40 fsw into a 15 min period at 50 fsw and a 15 min period at 40 fsw
- Increase the maximum number of O_2-breathing periods from 4 to 8:
  - Periods 2 through 4 at 40 fsw
  - Periods 5 through 8 at 30 fsw

The impact of these changes is illustrated in Figure 6.

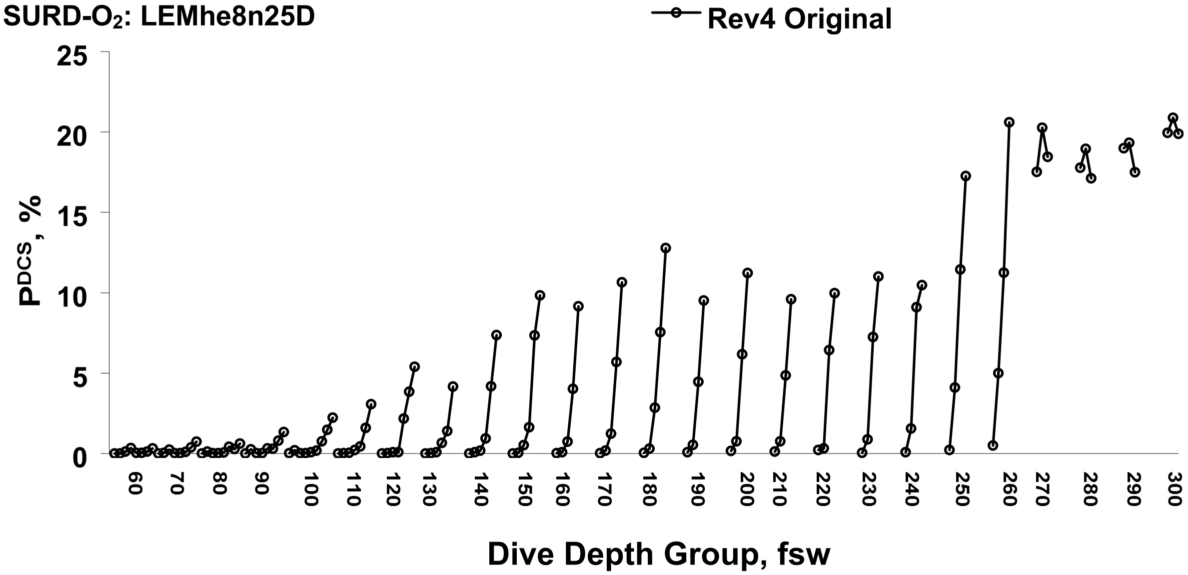

Figure 5. LEMhe8n25-estimated DCS risks of surface-supplied He-O_2 surface decompression on oxygen (sur-D-O_2) schedules in U.S. Navy Diving Manual, Revision 4.

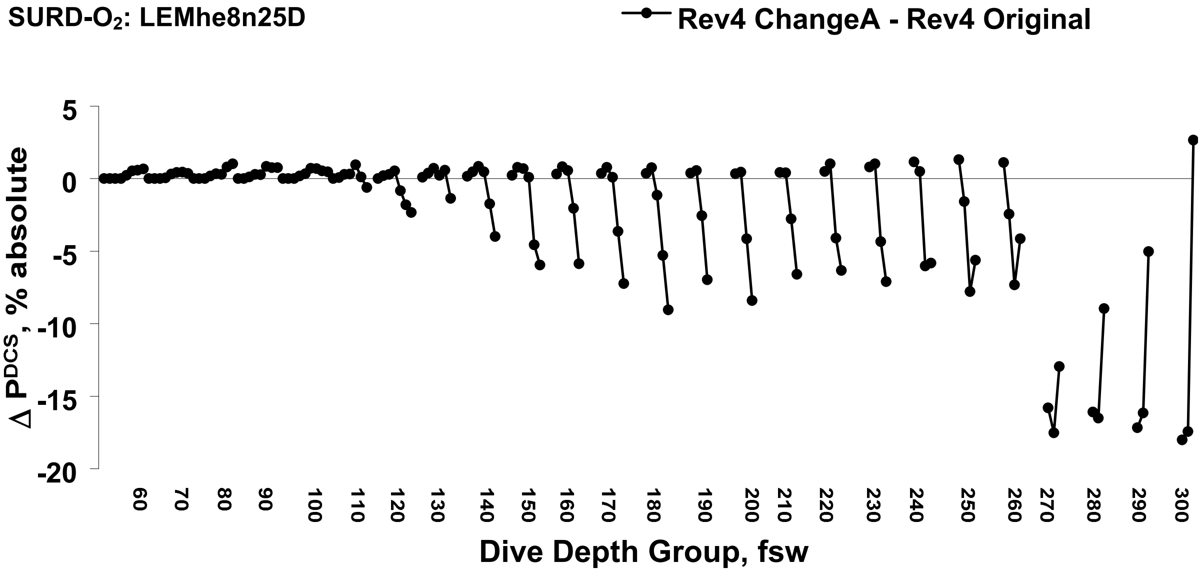

Figure 6. LEMhe8n25-estimated DCS risk changes caused by modifications designed to reduce risks of in-water CNS O_2 toxicity in 1999 Revision 4 surface-supplied He-O_2 sur-D-O_2 tables.

The decreases in O_2 toxicity risk arising from changes to the in-water decompression procedures propagated into the sur-D-O_2 procedures as well, as shown in Figures 7 and 8.

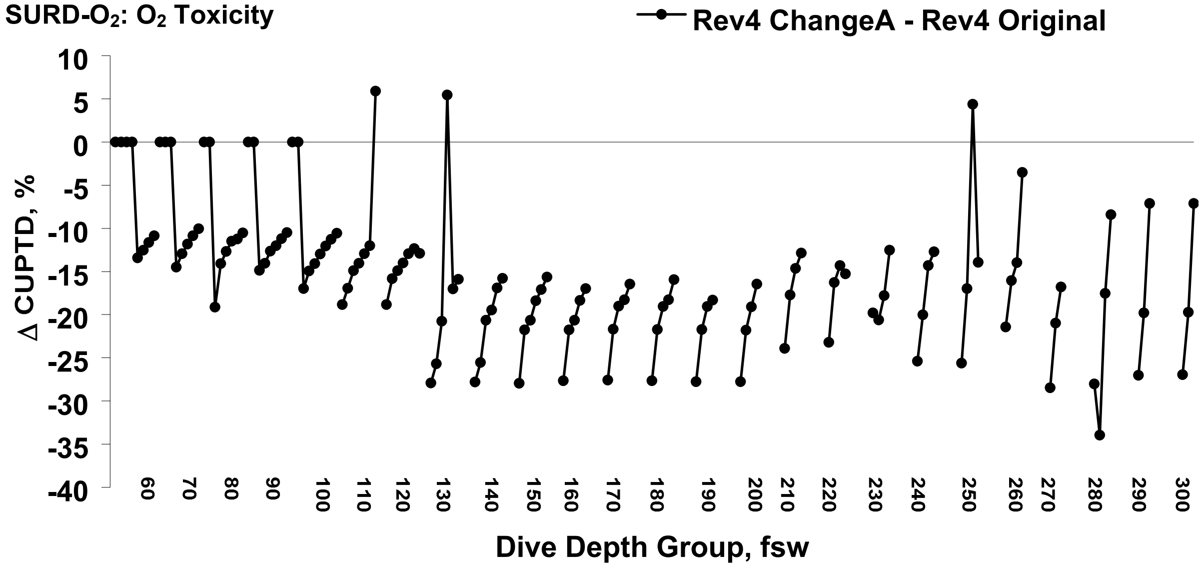

Figure 7. Changes in cumulative unit pulmonary toxic dose (CUPTD) caused by modifications designed to reduce risks of in-water CNS O_2 toxicity in 1999 Revision 4 surface-supplied He-O_2 sur-D-O_2 tables.

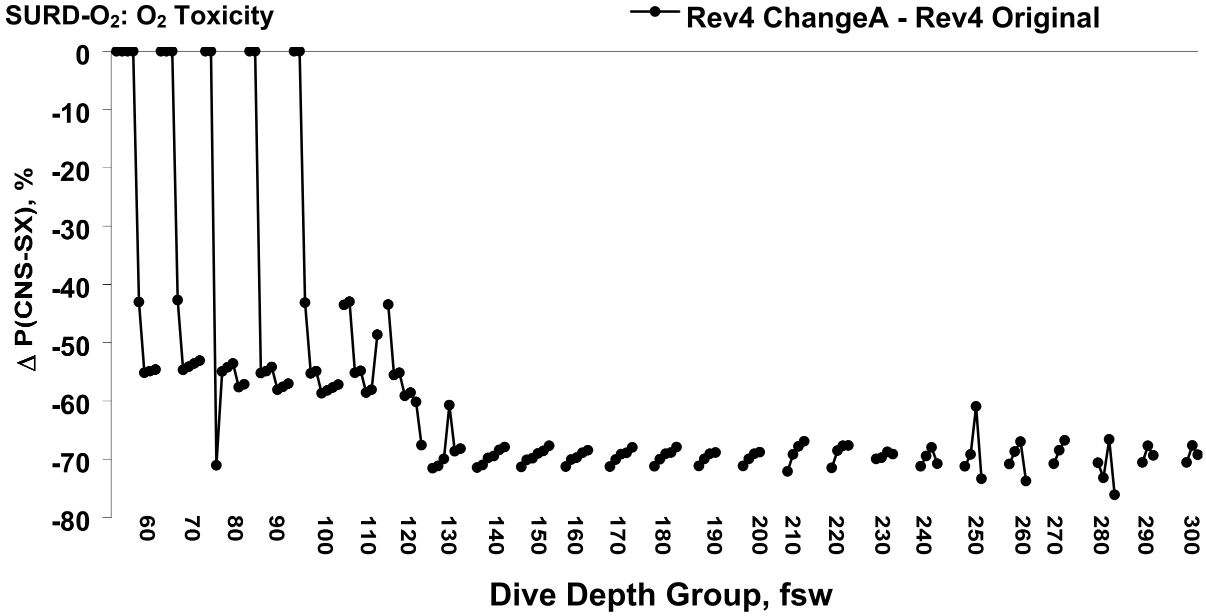

Figure 8. Decreases in estimated overall risks of seizure caused by modifications designed to reduce risks of in-water CNS O_2 toxicity in 1999 Revision 4 surface-supplied He-O_2 sur-D-O_2 tables.

The modified tables were field tested in surface-supplied He-O_2 dives on the USS *Monitor* in summer 2000. More than 150 dives were completed with sur-D-O_2 procedures to depths of 220 – 240 fsw with bottom times up to 40 min. No symptoms or signs of CNS O_2 toxicity and two cases of DCS occurred. The DCS incidence was considered well within acceptable limits, especially in view of the heavy workloads that divers sustained both during and after the dives. The modified tables were published in the U.S. Navy Diving Manual, Revision 4, Change A issued 1-March-2001.

Summary

Documented U.S. Navy operational experience with surface-supplied He-O_2 diving since 1970 is relatively limited, and confined largely to dives to depths less than 250 fsw with sur-D-O_2. A series of *post hoc* changes to decompression tables last computed from first principles by Workman in the mid 1960's have been made to mitigate the risks of DCS and CNS O_2 toxicity in current U.S. Navy surface-supplied He-O_2 diving procedures. However, such risks remain that, though presently acceptable by the U.S. Navy diving community, may not be acceptable to the more conservative scientific diving community. It may be time to develop a new set of decompression tables for surface-supplied He-O_2 diving from first principles with modern probabilistic approaches to decompression. DCS risk will likely remain an issue in surface-supplied He-O_2 diving with operationally acceptable bottom times and in-water decompression, particularly for dives to depths deeper than 250 fsw.

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BIOMEDICAL AND OPERATIONAL CONSIDERATIONS FOR SURFACE-SUPPLIED MIXED-GAS DIVING TO 300 FSW

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Introduction

Surfaced-supplied mixed-gas diving to 300 fsw would significantly extend the depth capabilities of the scientific diving community beyond the limitations of air and nitrox diving. Closed-circuit mixed-gas rebreathers offer some unique advantages including, but not limited to, the ability to perform constant oxygen partial pressure dives with subsequent decompression advantage and minimal deck space requirements for the support vessel. However, there are disadvantages with rebreathers including safety, equipment maintenance, and diver proficiency levels necessary to conduct safe operations. Surface-supplied mixed gas offers some unique capabilities that may be useful for a range of scientific diving operations.

The ability to efficiently train scuba divers to use surface-supplied diving techniques (Fig. 1) under the supervision of an experienced support team has recently been demonstrated with the NASA NEEMO 8 (NASA Extreme Environment Mission Operations) mission conducted in March of 2005.

Figure 1. Surface-supplied diving techniques from air saturation.

On this mission, three divers with no previous experience in surface-supplied diving techniques were able to undergo a short training program and safely use surface-supplied diving techniques to make excursion dives from air saturation at 50 fsw in the NOAA Aquarius Habitat.

Physiological and Operational Considerations

The following is a brief overview of physiological considerations associated with surface-supplied mixed-gas diving, which include, but are not limited to:

Oxygen Toxicity

The potential for both acute and chronic oxygen toxicity requires careful attention to the selection, mixing, and monitoring of bottom, in-water, and chamber decompression gases. Control of oxygen partial pressure is necessary for the individual dives as well as control of multi-day oxygen Unit Pulmonary Toxicity Doses (UPTDs). Standard and field-proven techniques are well established for these practices.

Thermal Stresses

The increased thermal conductivity of helium can increase respiratory heat loss and depending on water temperature can drive the need for dry or hot water suits and even respiratory gas heaters under extreme cold water temperature conditions.

Speech

Helium is well known to cause speech distortion. Use of helium unscrambler radios is a requirement to maintain clear communications between the dive supervisor and the diver.

Isobaric Counter Diffusion

Depending on the depth and bottom time, up to four different breathing gases can be used on the same dive. A typical dive profile might utilize a 12% heliox mix on the bottom at 300 fsw, followed by switches to air at 150 fsw, to 50/50 nitrox at 50 fsw, and to 100 % oxygen in a deck decompression chamber during the surface decompression portion of the dive. When inert gases are switched there is always the potential of isobaric counter diffusion in localized tissue areas due to the asymmetry between the mass transfer coefficients of the two different inert gases (Harvey and Lambertsen, 1976). Generally, isobaric counter diffusion becomes a problem on very deep and long dives that require long decompressions (such as commercial bell-bounce dives) and would not generally be considered a problem for the bottom times and depth ranges considered for scientific diving.

Work of Breathing and CO_2 control

Proper pulmonary ventilation is required to eliminate CO_2 and provide sufficient tissue oxygenation to meet the metabolic needs of the working diver. The demands of the gas delivery system increase with depth. Most commercial diving helmets or band masks provide both a demand and free-flow gas delivery and have been well proven in the depth ranges and workloads associated with scientific diving to 300 fsw.

Narcosis

Nitrogen narcosis is a consideration for surface-supplied mixed gas diving. Most of the widely used decompression tables utilize a gas switch from heliox to air as deep as 150 fsw.

Decompression

The decompression requirements associated with 300 fsw mixed gas dives are considerable, even with short bottom times of 20 minutes. Helium has faster uptake and elimination kinetics than nitrogen (for most tissue types) and, therefore, direct ascent to the surface in response to an equipment malfunction is not a viable option. Decompression techniques are varied and include numerous options: breathing gases combined with diver deployment and recovery (open and closed bells) and in-water versus surface decompression.

Operational Considerations for Surface-Supplied Mixed Gas Diving

Table 1 provides an overview of the many operational considerations associated with surface-supplied mixed gas diving.

Table 1. Operational considerations.

▪ Type of vessel and mooring system ▪ Deck space, crew support ▪ Stable platform for diver deployment and recovery	Consumables and logistics ▪ Demand/open circuit heliox versus gas reclaim ▪ Closed and semi-closed breathing systems ▪ Significant logistics considerations
▪ Diver thermal protection ▪ Wet suit, dry suit, hot water suit ▪ Gas heating	▪ Gas supplies/mixing vs. premix, minimum 02 concentration limits
▪ Diver deployment/recovery systems ▪ Stage, open-bottom bell, closed bell ▪ Scientific equipment deployment and recovery	Umbilical management ▪ Diver and/or diving bell ▪ Location of vessel versus worksite ▪ Interactions of umbilicals with marine environment and scientific equipment
▪ Deck decompression chamber system ▪ Surface decompression, treatment, number of chambers	▪ Oxygen cleaning/compatibility ▪ High pressure versus cryogenic storage ▪ Boost and transfer pumps
▪ Bail out system ▪ Air ▪ Mixed gas ▪ Potential for misusing can result in hypoxia or acute O_2 toxicity	Training level ▪ Diving supervisors, rack operators, life support techs ▪ Training and proficiency for scientific divers

▪ Standard operating procedures; diving safety manuals; dive recording and reporting ▪ Decompression procedures	Contingency planning/operations ▪ Emergency decompression ▪ Omitted decompression

Surface-supplied mixed gas diving is an order of magnitude more complex than air or nitrox scuba diving, and a professional dive support team will be a requirement for safe operations.

Surface-Supplied Mixed-Gas Decompression Tables

Commercial diving companies use a variety of surface mixed-gas decompression tables, most of which are based on some variation of the U.S. Navy (USN) helium partial pressure tables. Typically, the diving companies do not use 100% oxygen for the 40 fsw in-water decompression stop. There are various modifications that include doubling the 40 fsw stop time on air for both the 50 fsw and 40 fsw stops, while some companies utilize a 50/50 nitrox decompression gas for the 50 and 40 fsw stops to increase conservatism.

The USN partial pressure tables and the majority of the commercial diving mixed-gas decompression tables are based on variations of the Haldane/Workman decompression model. This model incorporates the same perfusion-limited exponential inert gas exchange model as the original Haldane model. However, instead of using the Haldane pressure reduction ratio as a measure of decompression stress, Workman utilized a critical pressure difference between the calculated tissue nitrogen partial pressure and the surrounding hydrostatic pressure as a criterion for safe decompression stress.

This tolerable supersaturation is referred to as an M-value. In Workman's model, each half-time tissue has its own M-value, with the M-values decreasing as the half time increases. Each M-value is allowed to increase with depth at a linear rate defined by a delta M-value. Most of the models used in commercial diving incorporate twelve tissue half times, each with its own M-value and delta M-value. There are different M-values for nitrogen and helium, with helium M-values allowing greater supersaturation. On mixed gas dives that incorporate air decompression the effective M-value is calculated based on the proportion of tissue helium and nitrogen tension. Because the Haldane/Workman model has multiple degrees of freedom, it is very adaptable at incorporating the results of diving experience and new laboratory trials by changing the parameters within the model to make it "fit" the diving data. Even though the DCS incidence associated with tables based on this model is generally low (well under 5%) for most of the commercial diving companies (Lambertsen, 1991), there is a pattern of increasing DCS incidence with increasing time and depth of the dives. This pattern was shown in an epidemiological study of DCS incidence in North Sea diving (Figure 2).

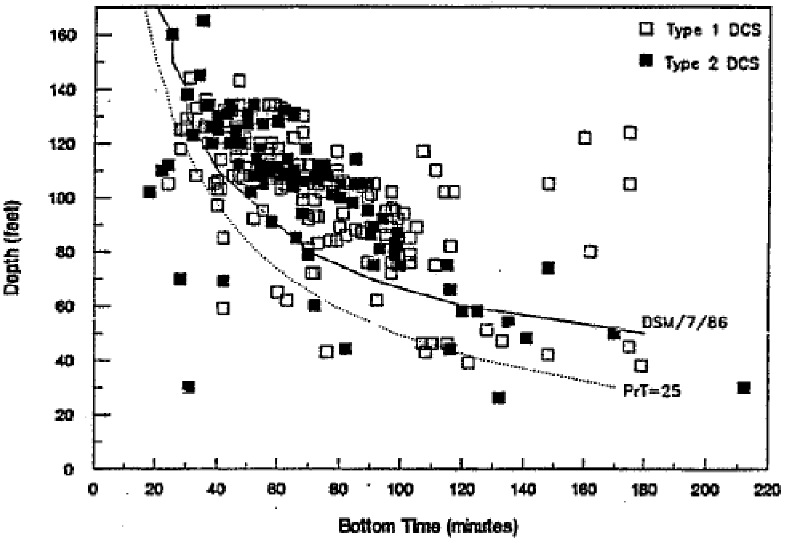


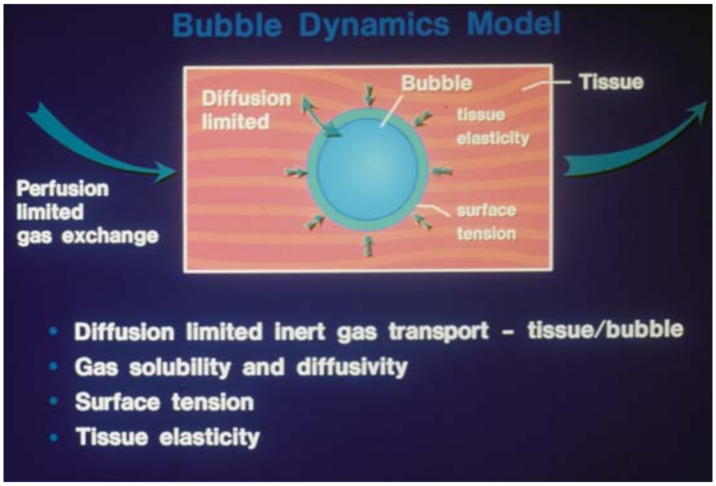
Figure 2. Distribution of DCS incidents associated with North Sea commercial diving operations (Shields *et al*, 1989).

One of the limitations of the Haldane/Workman model is that it does not directly model separated gas phase, but assumes that as long as the supersaturation is controlled to the M-value limits there will be no gas phase separation and no DCS. There is an abundance of data that indicates gas phase separation and growth occurs prior to symptoms of DCS. Decompression stress would therefore be better managed by controlling the size or volume of gas bubbles, rather than the supersaturation. In practice, the parameters of the Haldane/Workman model have empirically evolved to approximate gas bubble control. However, since the model does not directly model bubble growth, it is very limited in its ability to extrapolate to longer and deeper depths or new dive profiles that are outside the database on which the model was calibrated.

Tissue Bubble Dynamics Model

In order to address the limitations of the Haldane/Workman model, the Tissue Bubble Dynamics Model (Gernhardt, 1988; 1991) was developed based on first principles to provide a model to control decompression stresses based on the tissue bubble dynamics. A graphic description of the model is show below in Figure 3.

The TBDM incorporates a perfusion-limited gas exchange between the lungs and the tissue, combined with a diffusion-limited gas exchange through a diffusion barrier between the bubble and the well stirred tissue. The model accounts for gas solubility and diffusivity in various tissues as well as the surface tension and tissue elasticity. The model was retrospectively validated by statistical analysis of 6457 laboratory dives which resulted in 430 cases of DCS (Lambertsen *et al,* 1991) using the logistic regression method (Lee, 1980). The decompression data (provided by the International Diving, Hyperbaric Therapy and Aerospace Data Center) included a wide range of decompression techniques. Data sets were combined based on the likelihood ratio test. The results of the statistical analysis are shown below in Table 2.



Bubble Dynamics Model

- Diffusion limited inert gas transport - tissue/bubble
- Gas solubility and diffusivity
- Surface tension
- Tissue elasticity

Figure 3. Tissue Bubble Dynamics Model (TBDM)

Table 2. Results of logistic regression analysis of 6547 laboratory decompression dives. Goodness of fit was calculated using the Hosmer and Lemeshow Goodness-of-Fit Test.

Data set: In-water decompression on air		Test for improvement		Test for goodness of fit	
Index	Log-likelihood	x2	p-value	x2	p-value/ Df*
Null set	-529				
Bubble growth Index	-498	62.8	.000	4.8	0.77/8
Relative supersaturation	-524	10.8	.001	19.4	0.08/12
Exposure index	.505	47.9	.000	30.5	0.00/9

The Bubble Growth Index provided a significant and better prediction of the data than either supersaturation or the Hempleman exposure phase index (Hempleman, 1952). It also provided the very good fit of the data based on the Hosmer and Lemeshow goodness of fit test (significance p>.05). The DCS incidence data associated with different degrees of theoretical bubble growth were plotted as a histogram in Figure 4. The x-axis denotes the bubble growth index (the maximum bubble radius in any tissue compartment divided by the initial radius) and the y-axis denotes the associated DCS incidence. The number of dives associated with each interval is shown at the top of each bar.

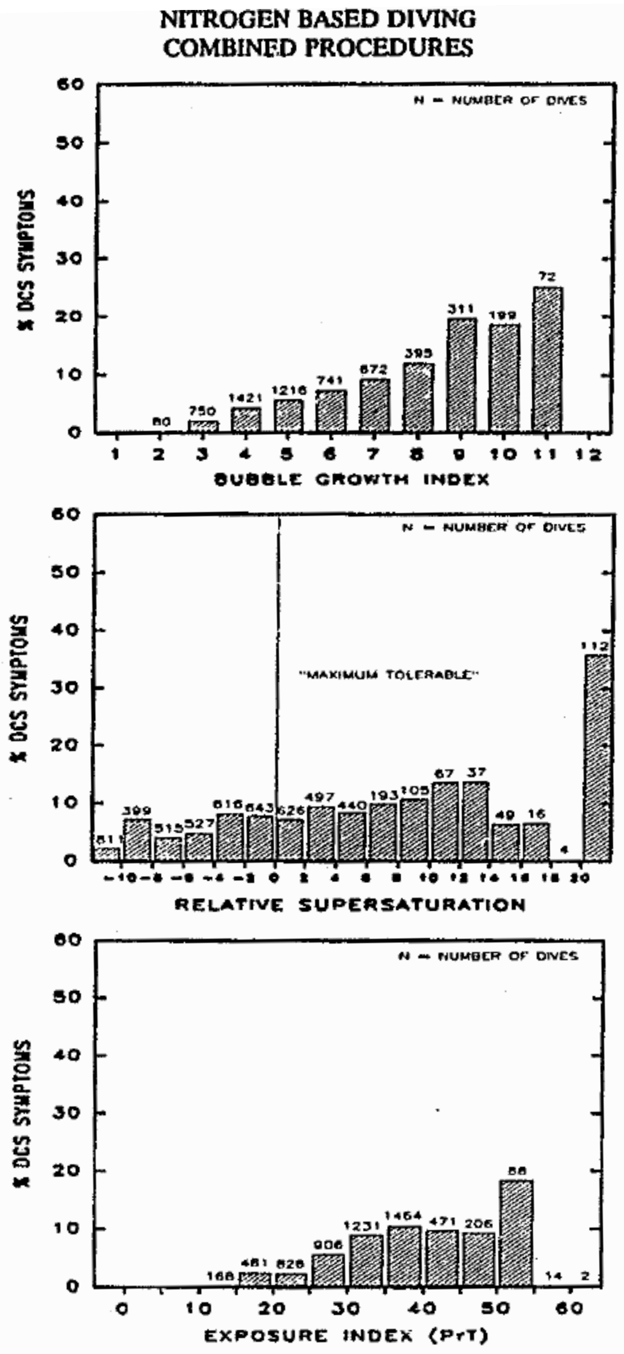


Figure 4. Histogram of DCS incidence versus decompression stress index (Bubble Growth Index, Supersaturation, and Exposure Index (pressure x square root of time.)

The TBDM was used to generate new surface decompression tables. These were tested in a limited laboratory trial, followed by sea trials with time/depth recorders and post-dive Doppler VGE measurement, followed by routine operations.

Table 3. Results of laboratory trials of the Bubble Dynamics Tables

Profile fsw/min	n	DCS	VGE (Grade 3, 4)
90/80	6	0	0
120/40	6	0	1: Grade 4
130/40	3	0	0
150/40	9	0	3: Grade 3
Total	24	0	4 (16%)

Table 4. Results of sea trials and operational use (phase IV) of the Bubble Dynamics Tables. Many of these dives were in the USN extreme exposure range.

Phase	Decompression procedure	Offshore dives	DCS incidents	DCS %
III	*No Decompression*	20,000	0	0%
III 1993-5	Air sur-D-O_2 With N_2O_2	4,000 500	9	.2%
IV (ops)	Air sur-D-O_2 and multi-depth	2,500	1	.04%

The final operational implementation resulted in less than .1 % DCS on dives with depth and bottom times in the extreme exposure range of the USN standard air tables. These decompression tables were based on controlling the bubble growth index to ≤ 2.8.

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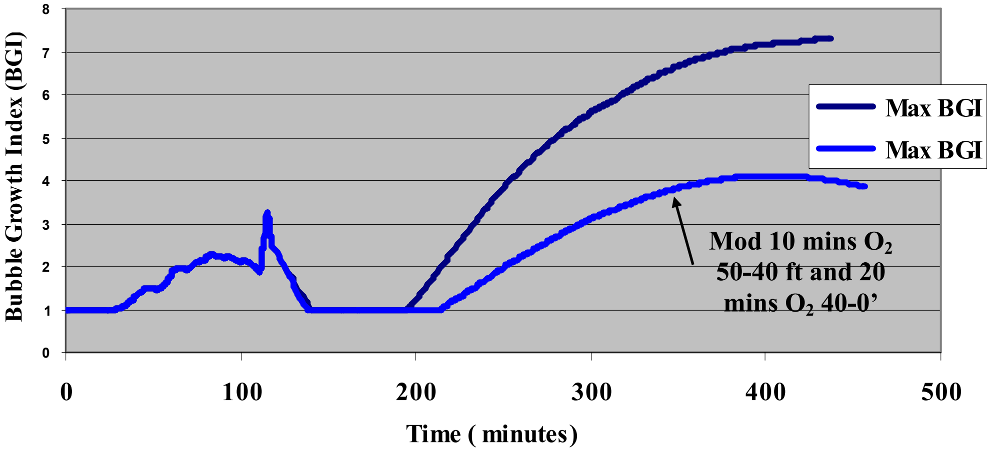

Figure 5. Bubble Growth Index for Oceaneering Alpha Table 300 fsw/15 minutes on 90% helium, 10% oxygen bottom mix, with and without conservative field modifications to chamber sur-D-O_2 decompression.

The TBDM was used to analyze commercial diving surface-based mixed gas decompression tables. The mixed gas decompression tables that have the best reputation for low DCS incidence are the Oceaneering Alpha tablesMany of the published decompression tables are conservatively modified for field operations. One common modification was to increase the ascent time from 50 to 40 fsw during chamber O_2 breathing from 2 to 10 minutes and to increase the ascent from 40 fsw to the surface from 10 to 20 minutes. Figure 5 shows the bubble growth index for the published and field-modified table.

Work Efficiency Index

For this 15 minute bottom time the decompression requirement was 67 minutes of in-water decompression followed by 69 minutes of chamber decompression. The work efficiency index (Gernhardt, 1991) of this dive defined as bottom time/total decompression time was .11. It is clear that the work efficiency of deep mixed gas diving is not very high. Table 5 below compares the work efficiency indices of various forms of diving.

Table 5. Diving method and depth versus Work Efficiency Index (WEI)

Dive type	Depth range (fsw)	Work efficiency index (WEI) = bottom time/deco time
sur-D-O_2(single depth)	70-170	.5-.65
Repet-up	40-190	.8-1.0
sur-D-O_2 (multi-depth)	30-190	1.75- 2.0
sur-D-O_2 (HeO_2)	200-300	.1- .4
Multi-depth, multi-gas	30-300	1.0 -3.5
HeO_2 saturation	300-1000	3-10 (10-30 Days)
Air Saturation (Aquarius)	50	3.8-4.7

Multi-Depth/Multi-Gas Decompression Tables

There are significant decompression advantages associated with multi-depth diving that have been well utilized by the sport, scientific, and commercial diving industries. It is also well documented that appropriately switching inert gases can result in a decompression advantage. The USN Helium Partial Pressure Tables and virtually all of the commercial diving mixed gas tables incorporate a switch from HeO_2 to air at various depths. The off-gassing gradients of an individual gas species are determined by the difference between the partial pressure of the inspired inert gas and the tension of that gas dissolved in the tissues. Each gas will diffuse into or out of the tissue under its own electrochemical potential gradient. Switching from helium- oxygen to nitrox results in a net decompression advantage as the helium will be eliminated faster than the nitrogen is absorbed (in the majority of body tissues). Combining the decompression advantages of multiple depth diving with inert gas switches can significantly improve the work efficiency index of mixed gas diving. Since some, if not many, scientific diving operations would involve study of marine life along a wall, this method of diving would be well suited to optimizing the science return from a given dive. Figure 6 shows the bubble growth index of a multi-gas/multi-depth dive to 300 fsw.

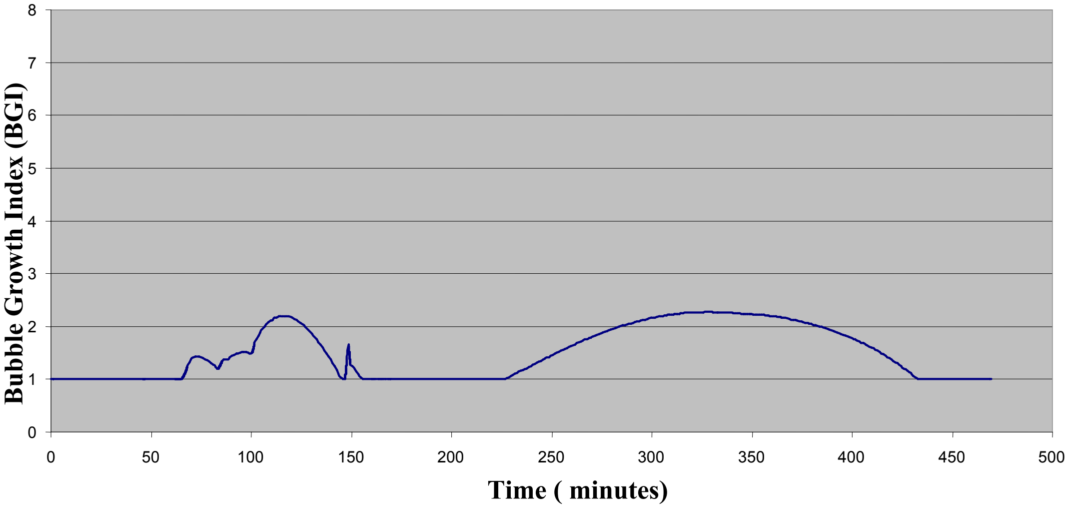

Figure 6. Bubble Growth Index associated with a 300 fsw multi-depth/multi-gas decompression: 40'/45 mins-air; 300'/15 mins-HeO_2; 150'/15 mins-air; 90'/15 mins-air; 60'/45 mins-50/50 nitrox.

This dive profile would start with a 45 minute air dive at 40 fsw, a switch to HeO_2 for a 15 minute exposure at 300 fsw, followed by a switch back to air for working at 150 and 90 fsw with a final switch to a 50/50 nitrox mix at 60 fsw. This type of dive profile provides for significant bottom time across a depth range from 40 - 300 fsw and results in a total bottom time of 105 minutes with no in-water decompression and an 80-minute surface decompression on oxygen. The resulting work efficiency index (WEI) is 1.3 versus .11 for the equivalent single-depth dive of 15 minutes at 300 fsw. The bubble growth index is controlled at less than the 2.8 level used for the successful Bubble Dynamics Tables that resulted in less than .2% DCS on over 7000 operational dives, many of which were USN extreme exposure profiles.

This analysis suggests significant operational and safety advantages associated with this type of diving. There have been limited, but successful, field experiences with this type of dive profile in commercial diving operations. Development of multi-gas/multi-depth decompression tables for scientific diving would require careful analysis of the mission profiles, followed by appropriate laboratory testing and controlled sea trials.

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OPTIMAL DECOMPRESSION FROM 90 MSW

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Introduction

> *" The key to making technical trimix diving practical was the ability to perform an efficient and reliable decompression from a dive with minimal narcosis and without posing a substantial risk of oxygen toxicity"*
> *Hamilton and Thalmann (2004).*

The aim of all decompression procedures is to reduce the risk of serious injury, in particular to the central nervous system, to an acceptable level. Furthermore, decompression time should be reduced as much as possible without increased risk. These requirements are generally accepted as being mutually exclusive. However, a recent paper from our group demonstrated experimentally that a significant reduction in decompression time can be achieved with a dramatic reduction in bubble formation (Brubakk, *et al.* 2003). These results indicate that it should be possible to develop an optimal decompression profile.

It is generally accepted that the risk of injury following decompression is related to the formation of gas bubbles as gas comes out of solution. A large number of different decompression models have been developed to describe the relationship between gas elimination and the formation of bubbles. There have been, however, few efforts to develop methods for optimizing the formulation of procedures from these models.

The currently implemented decompression models iteratively calculate the time to stay at each depth based on either supersaturation criteria or on bubble growth suppression criteria. Using this approach, there is no guarantee that the optimal profile is calculated. Both experimental evidence and bubble growth theory show that bubble growth is initiated at the start of decompression, but that critical separated gas volumes and clinical problems occur at the end of decompression or after the surface has been reached. With a chosen critical risk level for decompression sickness (DCS) based on evolved bubble spectra, the solution is not trivial due to higher order bubble dynamics. Dynamic optimization techniques can be used to optimize the decompression profile based on the model response over a prediction horizon. This method allows calculation of both the optimal stop times as well as the depth where these stops should be made.

The 90 MSW Scientific Dive

Long and deep bounce dives raise some very difficult questions. Using the method developed by Hennessy and Hempelman (1977), the risk for DCS can be calculated from the formula p√t, where p is pressure in bar and t is time in minutes. The study by Childs *et al* (1977) on commercial divers in the North Sea showed that the risk of DCS increased significantly above a p√t of 25. This increase was found irrespective of type of dive or decompression procedure used. A dive to 90 msw for 25 minutes has a p√t of 50. From this, one can assume that any dive in this range can be considered a high risk dive, as reducing the time at depth to 10 minutes still will give us a p√t of 31.

Another problem is the exceptionally long decompression time that is needed under the current procedures. Following the USN procedures, a dive to 90 msw for 25 minutes requires 163 minutes of decompression, while a similar dive using DCIEM tables requires 159 minutes. About 90 minutes of this time is spent breathing oxygen.

In a series of trimix dives to 80 msw for 30 minutes, decompression required 140 minutes, about half of that on oxygen (Shreiner and Kelley, 1970). Furthermore, scientific diving requires exceptional safety and efficiency. This is due to the fact that scientific divers probably have the lowest incidence of DCS of any diving group and that each dive trip is a unique opportunity where diving accidents will be very un-welcome. Data from a commercial diving company shows an incidence of DCS following mixed gas bounce dives between 0.05 and 1.8 % in the time period 1998-2004 (Joar Gangenes, pers. comm.) The so-called "technical divers" regularly perform this type of dive, however, they accept higher risks and long decompressions with long periods of oxygen breathing. Most of these divers do not use computers or accepted tables and most decompression procedures are estimated based on the divers' personal experience (Unpubl. comm.).

For these dives, trimix (nitrogen-helium-oxygen) is the only viable option. To our knowledge, no good decompression models exist that take the properties of the three gases involved into account. Most commercial diving companies do not use mixed-gas bounce diving procedures for dives between 100 and 300 fsw due to the high risk of DCS (Hamilton and Thalmann, 2004). As the solubility and diffusivity of the two inert gases (nitrogen and helium) are quite different, there is a possible advantage of having continuous mixing during the dive. This is a technique that was used successfully by Bühlmann (1988) and also by a number of technical divers. Because of the risk of nitrogen narcosis, the maximum nitrogen tension of the breathing gas is given as 400 kPa and the maximum oxygen tension at 130 kPa to prevent oxygen toxicity. However, oxygen breathing is regularly used during decompression.

Evaluation of Decompression Procedures

If new procedures are to be introduced, the method for their evaluation is of critical importance. This is particularly important if the aim is to reduce the risk for serious DCS, as deliberately provoking neurological symptoms may be ethically unacceptable, even if immediate treatment is available. Serious (neurological) DCS will not be acceptable, but musculoskeletal DCS can be tolerated.

Until now, no procedures have been developed that can distinguish between the risk of serious and non-serious (musculoskeletal) DCS (Tikuisis and Gerth, 2003). This is in spite of the fact that the pathophysiology of these conditions probably is quite different. Musculoskeletal DCS is most likely a localized phenomenon, caused by bubble formation in joints and muscles, probably on tendons, joint capsules and fascia (Harvey *et al,* 1944). It is our hypothesis that the main cause of serious neurological injury related to diving is caused by vascular bubbles. A number of studies have shown that there is strong correlation between vascular bubbles observed in the right ventricle and the pulmonary artery, an open foramen ovale (PFO) and neurological CNS symptoms (Moon *et al,* 1989; Wilmshurst and Bryson, 2000). Furthermore, studies have shown that AV channels open in the lung following even light exercise, allowing small bubbles to pass through (Eldridge *et al,* 2004). Even if bubbles observable by ultrasound were not seen after an air dive (Dujic *et al,* 2005), reduction in arterial endothelial function does not seem to require observable arterial bubbles (Brubakk *et al*, 2005). Thus, an initial test of any new decompression procedures would be its ability to reduce pulmonary artery bubbles.

Optimization of Decompression

Optimization has until now been defined rather loosely, but once agreement on the risk is defined, mathematical methods can be used to precisely define the procedure that will keep the risk below a certain level.

Bubble theory predicts that deeper stops than those suggested by the supersaturation models will reduce bubble formation on surfacing. Experimental evidence also suggests that the shape of the decompression profile significantly will reduce bubble formation in spite of a significant reduction of the time used for decompression (Brubakk *et al,* 2003).

The Copernicus Model

Most decompression models have been evaluated using clinical symptoms of DCS as an endpoint. Due to the low incidence of DCS, this approach requires an extensive amount of empirical data to achieve statistical significance for accepted risk. The actual gas dynamics and mechanisms behind DCS are never validated. For this reason, these models give unsatisfactory results when their operating domain is extrapolated to more extreme exposures. The principle behind Copernicus is to incorporate additional measurements to support the validation of the model. As mentioned earlier, our hypothesis is that the evolution of vascular bubbles is strongly linked to the risk of serious DCS. To achieve a good prediction of DCS it is necessary to have a model that adequately describes the dissolved gas tensions, the distribution and growth of gas bubbles in the human body, and the mechanism for injury by the bubbles. The Copernicus model is developed to predict these vascular bubbles as accurately as possible, still having the necessary simplicity to allow efficient computational implementation. Using bubble formation instead of clinical symptoms as a measurable end-point allows us to implement a more reliable validation with less empirical data. With a reliable criterion for DCS based on this bubble formation it is possible to calculate safer and/or faster decompression profiles. It is an important comprehension to distinguish between extension of deco time (conservatism) and increased safety. Dynamic two-phase models show the significance of the shape of the deco profile in addition to the time spent on the ascent. Both experimental results, theoretical knowledge and experience from currently used bubble models indicate that the way of calculating decompression procedures should be completely rethought compared to the traditional Haldanean principle.

Optimization Strategy

We may think of the diver as a system (black box) with a set of inputs and outputs (Fig. 1). The inputs *u,* are the time-varying parameters that influence the dynamic process. The Copernicus model uses three input parameters: ambient pressure, breathing gas composition, and blood perfusion. During decompression we can manipulate the ambient pressure (depth) and the gas composition to achieve the wanted outcome. Blood perfusion is estimated through measurements and is not an input we want to control. The output of the model *x* describes the evolved bubble spectra in the body. The optimization problem is formulated to get the diver as fast as possible to the surface without letting the stress *y*, exceed an accepted threshold.

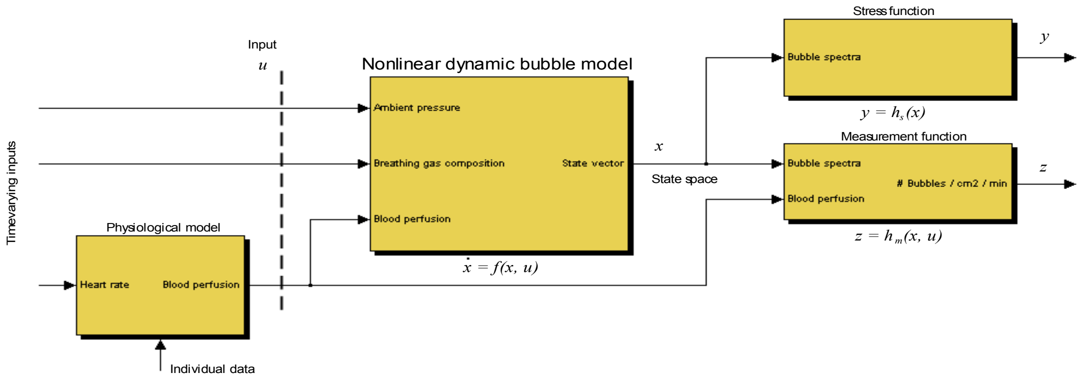

Figure 1. Schematic overview of the Copernicus model.

Optimizing Ascent Profile

Intuitively, the theoretical optimal solution would be a continuous depth profile or trajectory. However, such a solution is inconvenient for a diver to act in accordance with so a stepwise trajectory is preferable. We formulate the problem with a fixed number of stop-depths so the solution directly gives an optimal stepwise profile. Let us consider an assumed optimal decompression profile parameterization as shown in Figure 2

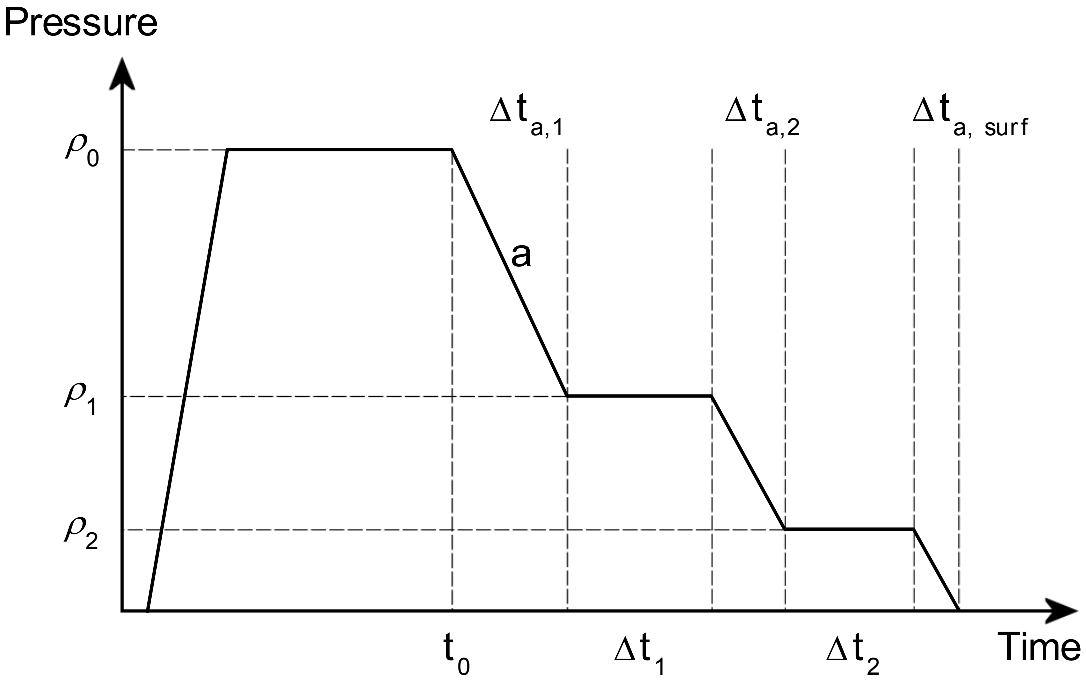

Figure 2. Parameterized decompression schedule.

The sum of all stop times is $t_{tot}=\sum \Delta t_i$ The optimization problem is formulated to minimize t_{tot} subject to a set of constraints. The constraint yields for the output of the model shown in Figure 1 and the formulation define the fastest possible combination of stop times that keeps the stress, y, under a set level. To solve such problems, general purpose SQP algorithms (sequential quadratic programming) may be used.

Optimizing Gas Mixtures

Figure 2 shows the calculation of the stop times, but any controllable, time-varying input parameter may be included to the optimization problem. The composition of the gas mix can be constantly changed in order to achieve the fastest possible decompression time. Currently we have no implementation of the calculation of optimal gas composition but simulations on the model using different compositions of helium, nitrogen, and oxygen have been performed. Figure 3 clearly shows how the model responds to manipulation of the breathing gas during decompression.

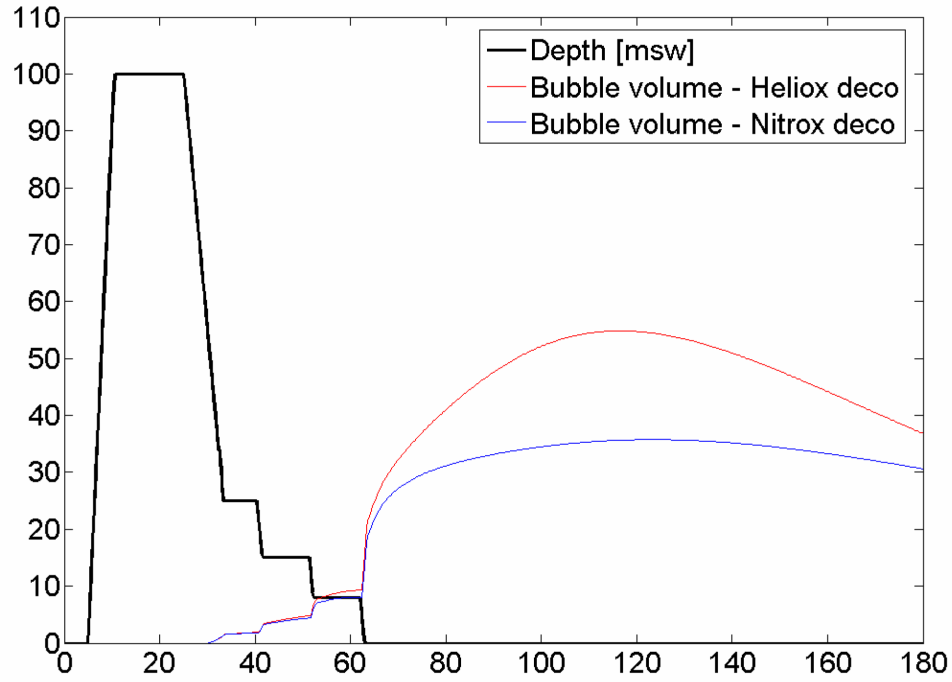

Figure 3. Simulation of bubble-volume in a 100 msw heliox dive following the same deco with different breathing gases. The upper blue line shows bubble-volume using 70% nitrox while the lower red line is using 70% heliox.

Example

To illustrate the principle we have simulated a dive to 42 msw for 20 minutes and bring the diver to the surface using only one decompression stop. We let the stop time and the depth be parameters to our optimization problem. Figure 4 shows the simulated decompression stress for a wide range of both stop times and depths. We can see that the decompression stress is constant for stop time $\Delta t_1=0$. This is the generated stress if the diver ascends directly to the surface. If the diver chooses to have his stop very deep, it will generate more stress, which comes as a result of increased gas uptake. The shallower he takes the stop, the more beneficial it becomes, until a certain point where the stop depth becomes too shallow to be efficient. The optimal point is somewhere in the hollow depending on the acceptable threshold of generated stress.

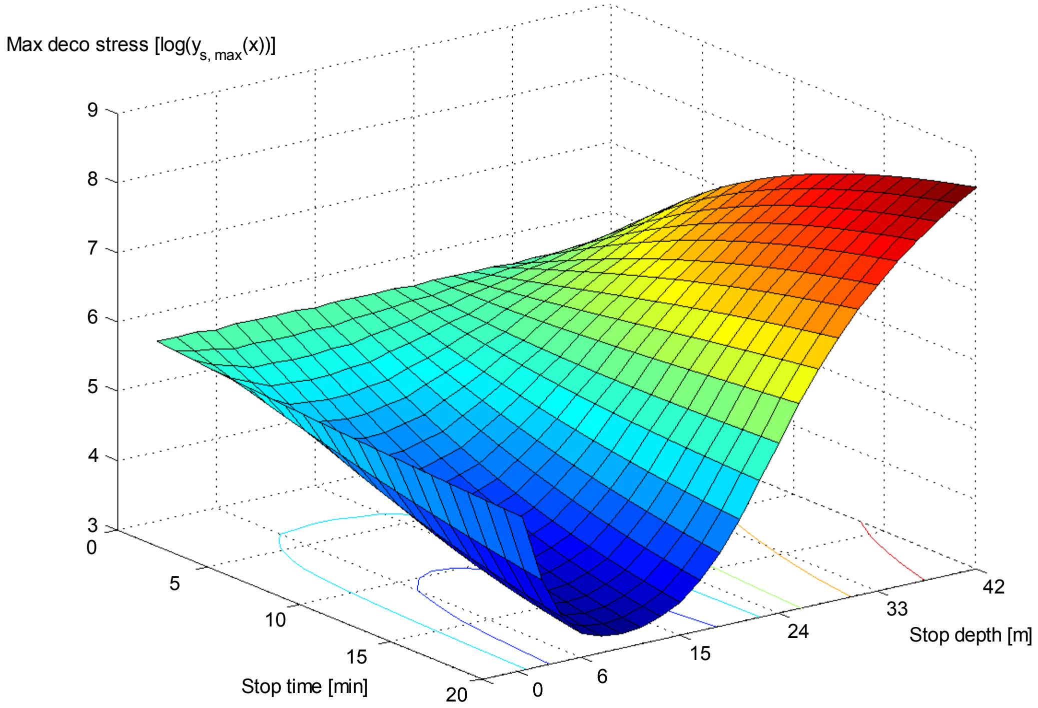

Figure 4. Simulated decompression stress for a range of stop times and depths for a single stop decompression case.

Future Work

The paper presented here shows how a four-phase model and optimization can be used for designing decompression profiles for deep mixed-gas diving. The optimization method is model independent, allowing easy comparison of how different models will influence actual dive procedures.

One significant advantage of the model is that it can incorporate new measurement modalities that can be used to modify diving behavior during the actual dives. From ultrasonic studies, it has been known for a long time that gas phase formation in the muscles is an early warning of DCS (Daniels, 1984). Recent new developments in ultrasound detection techniques can make on-line detection of tissue gas bubbles feasible.

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EVALUATION OF DIVE COMPUTER OPTIONS FOR POTENTIAL USE IN 300 FSW HELIOX/TRIMIX SURFACE SUPPLIED SCIENTIFIC DIVING

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This evaluation examined dive computer options to support scientific surface-supplied diving on heliox or trimix to depths up to 300 fsw. Four dive computers were determined to be able to operate under these conditions: the Cochran Undersea Technology EMC-20H, the Delta P Technology VR3, the Dive Rite NiTek He, and the HydroSpace Engineering HS Explorer. Decompression software that simulates the dive computers responses to profiles was obtained and scenarios for dives to 300 fsw for 20 minutes were calculated using heliox and trimix with various gas mixtures. Since the focus of this workshop is on surface-supplied diving, it is recommended that the primary use of dive computers be to provide depth, time, and ascent rate information to the diver and record the profile, leaving the diver's decompression to be controlled by surface-support personnel. Because of the rapidly increasing TDT debt for the additional 5-10 minutes of bottom time it is recommended that bottom times at 300 fsw be limited to 20 minutes. In relation to the high decompression debt incurred on these dives very serious concern needs to be given to potential blow-up situations, which can produce fatal decompression sickness. Various established heliox decompression tables are available for use in this type of diving. However, if the dive computer or decompression software options are chosen then, in lieu of studies that have validated the decompression algorithm, divers must have enough comfort and experience with the decompression algorithms and protocols they intend to use, in order to justify their use to their Diving Control Boards.

Overview

The objective of this paper is to evaluate available dive computer options to support scientific surface-supplied diving on heliox or trimix to depths up to 300 fsw and provide recommendations for their use. This was done by examining the decompression features of the currently available dive computers to find which would allow heliox or trimix diving to 300 fsw or deeper. Four dive computers were found to fit the criteria. The decompression features of these dive computers were reviewed to determine the decompression algorithms they used and what level of gas switching capabilities they had. In order to determine the decompression requirements of these dive computers in dives to the proposed operating depth of 300 fsw, decompression software that simulated their response was obtained.

The decompression software that purportedly emulated the various dive computers was used to calculate the response to specific 300 fsw/20 min total bottom time (TBT) dive scenarios. These scenarios included:

- Heliox dive without decompression gas switches
- Heliox dive with one gas switch to nitrox during decompression
- Heliox dive with gas switches two different nitrox mixes during decompression
- Trimix dive with gas switches two different nitrox mixes during decompression
- Heliox dive following the US Navy protocols
- Heliox dive following the DCIEM (now DRDC) protocols

The US Navy and DCIEM table comparisons were included to see how the computer simulations compared to established heliox tables. These simulations were run with settings that represented the dive computers in their most liberal decompression algorithm settings, as well as with the addition of safety factors available in the dive computers.

The total decompression time (TDT) obligation from the most liberal dive computer for a heliox dive without decompression gas switches was unacceptably long (5 hours). It was determined that multi-gas decompression protocols are required for more efficient operations. Switching to a single nitrox decompression reduced the TDT dramatically. Adding an additional nitrox mix did not make a significant difference. Moving to a trimix bottom mix with two nitrox mixes for decompression did have a major impact on reducing the TDT. For the trimix scenario the required decompressions for the four simulations of the computers, in their most liberal mode, were within eight minutes of each other (89-97 minutes).

Comparison of the computer simulations to the US Navy heliox decompression tables (using the gas mixtures and depth switches prescribed by the US Navy) showed that in the most liberal mode the EMC-20H and VR3 exceeded the TDT required by the US Navy tables. In its most conservative setting the HS Explorer was able to exceed the US Navy TDT requirement if the air breaks were omitted.

In their most liberal settings the simulated computer requiring the most decompression for the comparison to the DCIEM heliox table (using the gas mixtures and depth switches prescribed by the DCIEM tables) was the Delta P VR3. However, it's calculated total decompression time was still over 30 minutes shorter than the DCIEM tables. Only two of the simulated computers reached or exceed the DCIEM decompression requirements by adding in safety factors.

It is this author's opinion that in surface-supplied operations diver-carried dive computers are best used as a backup and that the major control of decompression should be assigned to the surface-support personnel using a preplanned set of tables that the dive computer emulates. In heliox operations there are established tables and protocols that are available, however, finding a computer that can be set to mirror their decompression requirements (both in total decompression time and decompression gas times) will prove difficult. In trimix operations software packages can be used to generate decompression tables that should closely reflect the dive computer's response. However, the paucity of data supporting the safety of models brings up risk management issues. In lieu of validation studies, organizations must have enough comfort with the decompression algorithms and protocols they use to be able to justify the use to their Diving Control Board. Concern also needs to be given to the potential of fatal decompression sickness in a blow-up situation.

Dive Computers

There are currently four dive computers on the market which will allow heliox and trimix diving to depths of 300 fsw:

- the EMC-20H – manufactured by Cochran Undersea Technology,
- the HS Explorer – manufactured by HydroSpace Engineering,
- the NiTek He – manufactured by Dive Rite, and
- the VR3 – manufactured by Delta P Technology

The manuals for these computers were obtained and reviewed for computer features and information regarding the decompression algorithms they utilize. There are many features of dive computers that can be compared. However, for this review the comparison is limited to decompression algorithms, number of gas mixtures, and any gas mixture limitations with regards to partial pressure of oxygen (PpO_2) or narcosis potential.

The following questions were e-mailed to the dive computer manufacturers regarding their dive computers and decompression algorithms:

- Have controlled human subject trials been performed to validate the decompression algorithm?
    - If yes, were any in the 300 fsw/20-30 min range?
    - If yes, have peer-reviewed papers been published on these trials and are reprints available?
- Do you collect documentation from uncontrolled (in the field) dives using this algorithm?
    - If yes, how many dives have been documented?
    - If yes, how much experience is there in the 300 fsw/20-30 min range?
    - If yes, what is the incidence of DCS that has been reported on this algorithm (if any)?

- Do you have a fuller description of the algorithm beyond what you have published in the manual and on your web site?
- Is there anything that you feel should be added to the description of the algorithm beyond what you have published in the manuals and on your web site?
- Is there a software package that will simulate the response of your dive computer to profiles?

The EMC-20H

The EMC-20H dive computer (Fig. 1) utilizes a "20 Tissue Adaptive Modified Haldanean" decompression algorithm. The computer adapts its algorithm in response to water temperature, rapid ascents ("microbubble"), and reverse profiles. The temperature adjustments are made in water cooler than 75° F and can be set to either "Normal" or "Reduced." In the "Reduced" mode the adjustment to the algorithm is about 150% of what it would be in "Normal" mode. There is no indication in the manual that the level of "microbubble" adjustment can be modified, but the reverse profile adjustment has the ability to be turned off. Additional conservatism from 0 – 50% can be set for the decompression algorithm. No information was available on the actual decompression algorithm or how the various adjustments modify the algorithm.

The user can enter up to three nitrox, heliox, or trimix gas mixtures. Limitations for the gas mixtures are 5.0 % to 99.9% oxygen in 0.1% increments and 0.0% to 95.0% helium in 0.1% increments. Gas switching in the calculations is determined by a preset minimum dive time and switch depths for both decompression mixes.

In their reply to the e-mail, Cochran reported that the Analyst 4.01P software would emulate the EMC-20H and sent a copy of it to be used in preparing this evaluation. They indicated that they were going to review the questions and follow-up with their answers, but at the time this paper is being written no further reply has been received.

The HS Explorer

The HS Explorer dive computer (Fig. 2) utilizes one of ten decompression algorithms. Seven of the algorithms are based on the Bühlmann ZH-L16C decompression model with differing degrees of offgassing asymmetry (100%, 118% and 135% of compartment ongassing half-time) and compartment gas loading allowances (100%, 97%, and 94% of ZH-L16C allowance). The other three algorithms are a "derivation of the Reduced Gas Bubble Model (RGBM)" with various levels of conservatism (100%, 97%, and 94% of model). The manufacturer had no validation information for the RGBM decompression algorithms and referred to Wienke's publications, which list various anecdotal reports supporting the efficacy of the model.

The user can enter up to ten nitrox, heliox, or trimix gas mixtures. Limitations for the gas mixtures are 5 % to 99% oxygen in 1% increments, 0 to 95% helium in 1% increments, and 0 to 79% nitrogen in 1% increments. Gas switching in the calculations is determined by a preset a descending or ascending gas switch depth for the different gas mixtures. At depth the diver manually confirms the gas switch.

Figure 1. Cochran Undersea Technology EMC-20H

Figure 2. HydroSpace Engineering HS Explorer

In their reply to the e-mail, HydroSpace Engineering answered that:

1. Dr. Wienke would be the person to contact regarding RGBM validation information
2. HydroSpace Engineering does not collect documentation from uncontrolled (in the field) dives using this algorithm. However, they did report that Dr. Wienke and Tim O'Leary have a number of dives in the 300 fsw depth range [1,136 in 200-300 fsw range] and that NAUI Tec is using RGBM exclusively. They reported that out of the people they know who have used the HS Explorer, nobody has reported any incidence of DCS.
3. Books by Dr. Wienke on RGBM were suggested for further information on the decompression model
4. HydroSpace Engineering did not answer question no. 4
5. They reported that the HS Explorer Simulator would simulate the ZH-L16C based algorithms and that GAP RGBM software would emulate the RGBM algorithms. The HS Explorer was obtained from their web site, but the cost of the GAP RGBM prevented its inclusion in this report.

The NiTek HE

Figure 3. Dive Rite NiTek HE

Figure 4. Delta P Technology VR3

The NiTek HE dive computer (Fig. 3) uses the Bühlmann ZH-L16C decompression model with no apparent way to modify the algorithm. No information was provided on the validity of the model.

The user can enter up to seven nitrox, heliox, or trimix gas mixtures. Limitations for the gas mixtures are 8 % to 99% oxygen in 1% increments, 0 to 92% helium in 1% increments. Gas switching in the calculations is done manually during the dive. A gas mix can not be locked into the dive computer if the PpO_2 is greater than 1.6 ata.

Dive Rite did not reply to the initial e-mailed questionnaire and a duplicate was sent with no response. However, based on information from various web sites it was concluded that Dive Rite's Dive Voyager Decompression Planning Software would emulate the NiTek He. A demo version of this software was obtained for the simulations in this report.

The VR3

The VR3 dive computer (Fig. 4) utilizes a decompression algorithm which is a "derivative of the Bühlmann ZHL 16 algorithm." It also contains "Deep-water microbubble controlling stops," which appear to be short one-minute stops taken halfway between the depth of the dive and the first model-based decompression stop, then halfway between the first deep stop and the first model-based decompression stop, continuing until the model-based stops are reached. The VR3 also allows a user-entered safety factor from 0 – 50%, which increases the inert gas content for calculations by 2% for every 10% increase in the safety factor. Only anecdotal information was provided to support the decompression algorithm's validity.

The VR3 has the ability to utilize ten gas mixes. One is permanently assigned to air and the user can enter up to nine nitrox, heliox, or trimix gas mixtures. If there were any limitations for the gas mixtures, no reference could be found in the VR3's literature. Gas switching in the calculations is determined by a preset descending or ascending gas switch depth for the different gas mixtures. At depth the diver manually confirms the gas switch.

In their reply to the e-mail Delta P Technology answered that:

1. No testing was done to validate the decompression algorithm.
2. VR3 does not collect data on uncontrolled dives, only emails saying things like "the whole team is fine after the project"
    a. None of the dives have been documented scientifically
    b. Delta P Technology reported that "the bulk of the diving is in the 60-70m range. However, we have a significant (300+) client base working in the 100m+ range"
    c. With regards to DCS incidence they stated, "General unpublished feedback is of no or little incidence of DCI. At this stage if we were getting significant [incidence] we would be definitely hearing about it and we are not"
3. Delta P Technology did not provide a fuller description of their algorithm because of concern about other people copying their product.
4. In terms of additional information about their decompression algorithm they stated, "The basic Bühlmann adaptation was put together in 1988. Since 2000, we put about 6000 units in the field, the majority working in the trimix mode".
5. They reported that Pro Planner software would simulate the response of the VR3. Delta P Technology provided a copy of Pro Planner to be used in preparation of this evaluation.

300 fsw Dive Scenarios

The dive scenarios selected to be simulated were based on various gas mixture combinations to the maximum depth of 300 fsw for 20 minutes. Initial simulations were made with the software emulating the dive computers algorithms' most liberal setting. The heliox simulations were based on running the gases PpO_2 close to 1.6 ata at their maximum depth of use. The trimix simulations were based on lower PpO_2 levels closer to what technical divers are using. Comparisons were also made with established US Navy and DCIEM heliox decompression tables using the same gas mixtures and gas switching depths indicated on the table. If any of the simulations did not meet or exceed the TDT requirements of the established table, then the software was adjusted until the TDT was met or the maximum level of conservatism was reached. Based on the adjustments that were made, the trimix dive was recalculated for 300 fsw/ 20, 25, and 30 min.

Heliox 15.9 – Single Gas

It was suggested that a single-gas heliox dive should be evaluated and that PpO_2 levels could reach 1.6 ata. Heliox 15.9 was selected to meet these criteria and a 300 fsw/20 min dive was simulated with the following conditions:

- Descent Rate 75 fsw/min.

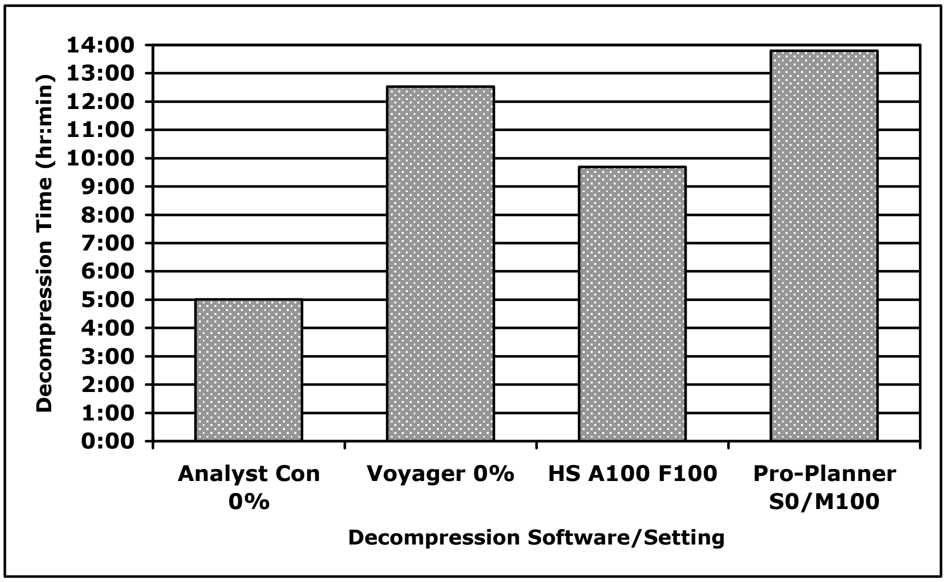

Figure 5. Decompression requirements for Heliox 15.9 300 fsw/20 min with no decompression gas switches.

- HeO_2 15.9 (0-300 fsw/300-0 fsw)
- Ascent Rate 30 fsw/min.

Decompression requirements resulting from this simulation ranged from 5 hours to almost 15 hours (Fig. 5). The long decompression requirements for a single heliox dive immediately eliminates it as a practical option.

Examining the depth of the first decompression stop for this scenario shows that the algorithms that state they control "microbubbles" produce deeper initial stops (Fig. 6).

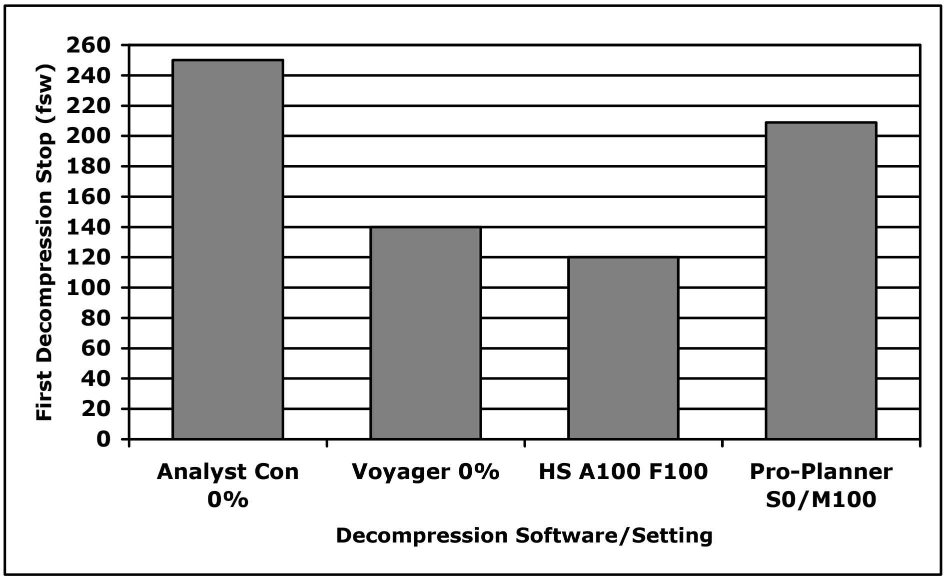

Figure 6. Depth of first decompression stop for Heliox 15.9 300 fsw/20 min dive.

Heliox 15.9 with EANx 50 decompression gas

In this scenario a decompression gas of 50/50 nitrox was added at decompression stops of 70 fsw and shallower. The PpO_2 of EANx 50 at 70 fsw is 1.56 ata. The addition of a single decompression mix greatly reduced the calculated TDTs to between 110 and 166 minutes (Fig. 7).

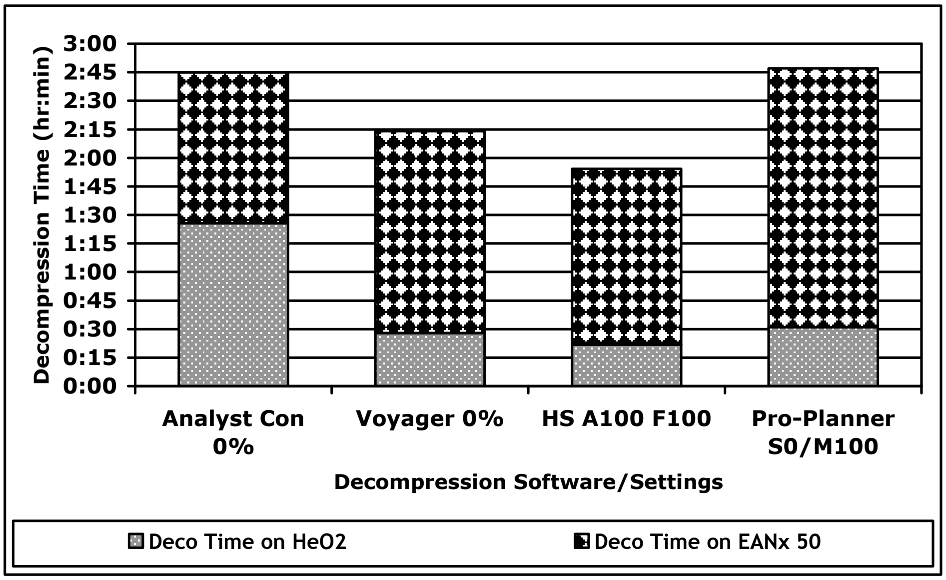

Figure 7. Decompression requirements for Heliox 15.9 300 fsw/20 min with EANx 50 at 70 fsw.

Heliox 15.9 with EANx 50 and EANx 80 as decompression gases

Adding nitrox 80/20 to the decompression at 30 fsw results in a PpO_2 of 1.53 ata, but does not significantly reduce the decompression requirements. The TDTs calculated with the addition of nitrox 80/20 were 99-154 minutes (Fig. 8).

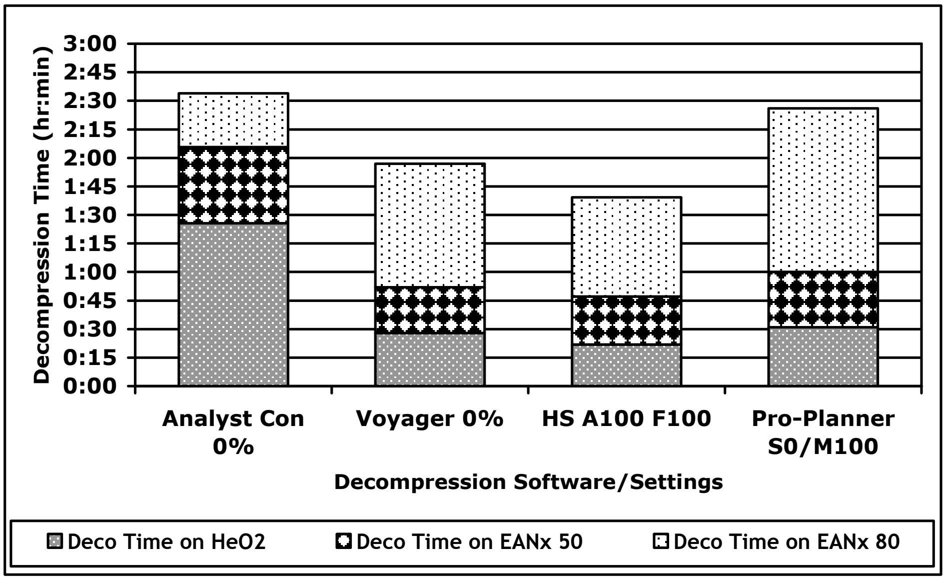

Figure 8. Decompression requirements for Heliox 15.9 300 fsw/20 min with EANx 50 at 70 fsw and EANx at 20 fsw.

Trimix 14/54 15.9 with EANx 50 and EANx 80 as decompression gases

A scenario was simulated based upon trimix with lower PpO_2s during the dive and at the end of the decompression. The bottom mix of trimix 14/54 gener

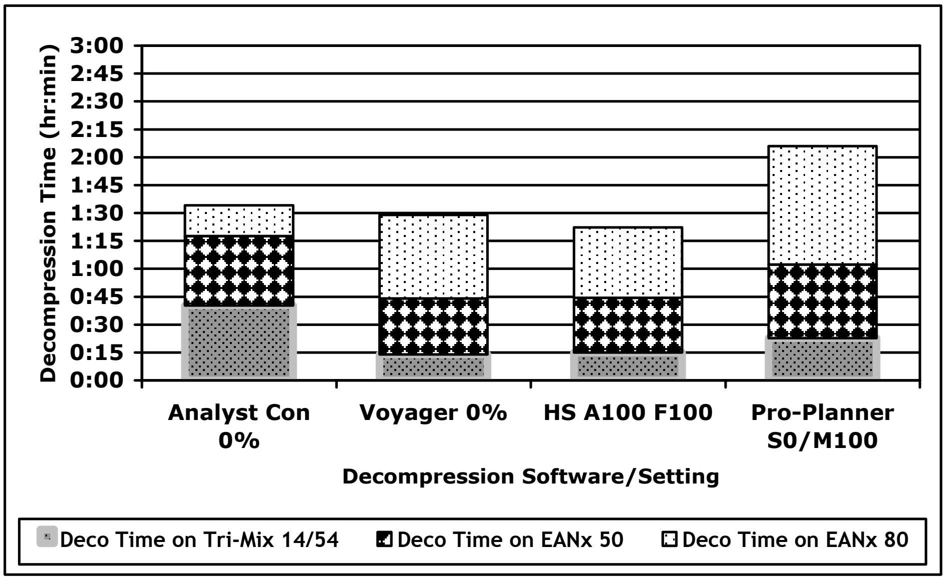

Figure 9. Decompression requirements for Trimix 14/54 300 fsw/20 min with EANx 50 at 70 fsw and EANx at 20 fsw.

ates a PpO_2 of 1.41 ata at 300 fsw and an equivalent narcotic depth of approximately 100 fsw. The nitrox 50/50 is used from 70 fsw to 20 fsw and the nitrox 80/20 is started at 20 fsw resulting in a PpO_2 of 1.28 ata. Even with the lower oxygen pressures the decompression requirements from all four programs dropped. The TDT range for this scenario was 82–126 minutes (Fig. 9).

Comparison to Established Heliox Decompression Tables

Since there is no hard evidence to suggest the level of safety associated with the decompression algorithms utilized in the dive computers and decompression software packages, a comparison was done with the established US Navy and DCIEM 300 fsw/20 min heliox decompression tables. The goal was to see if the decompression requirements of these tables were met, or exceeded, by the software simulations. If the requirements were not met then the algorithms that could be adjusted were set to either levels that met the table decompression requirement or to their maximum level of conservatism. Since, based on the available information, the NiTek HE algorithm is not adjustable; the Voyager software was not adjusted.

US Navy Heliox Tables

For the depth of 300 fsw the US Navy Heliox Tables use heliox 12.9/87.1, which results in a PpO_2 of 1.30 ata. To avoid hypoxia at the surface and on initial descent, air is breathed until a depth of 20 fsw. At 90 fsw decompression a switch is made to heliox 50/50, producing a PpO_2 of 1.86 ata. At 30 fsw oxygen is breathed (PpO_2 = 1.91 ata) and 5 minute air breaks are taken for every 30 minutes of oxygen breathing. The final decompression stop is at 20 fsw. The TDT for the US Navy 300 fsw/20 min heliox table is 160 minutes (including the air breaks).

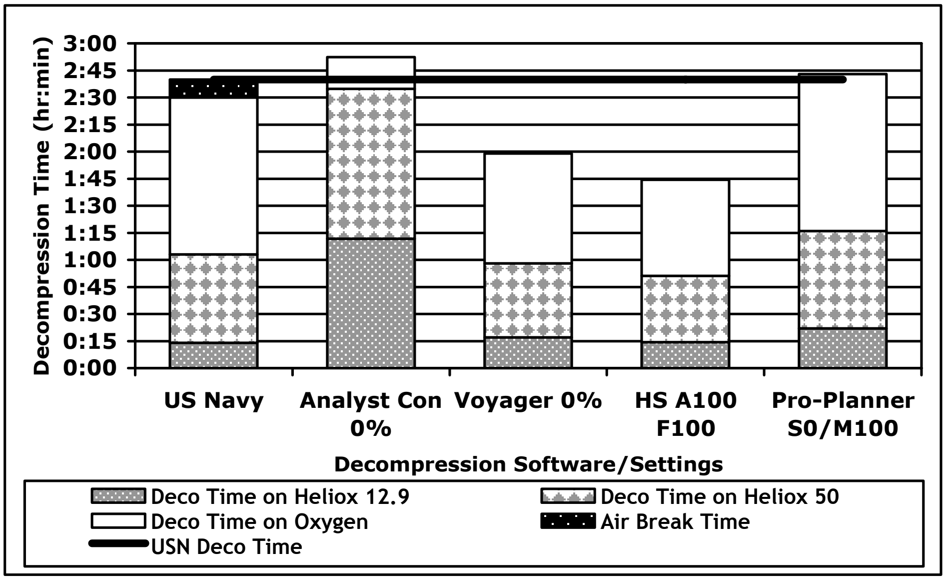

Figure 10. Decompression requirements for 300 fsw/20 min dive computer simulations vs. US Navy heliox tables.

The results from the simulations ranged from 104–172 minutes. The simul

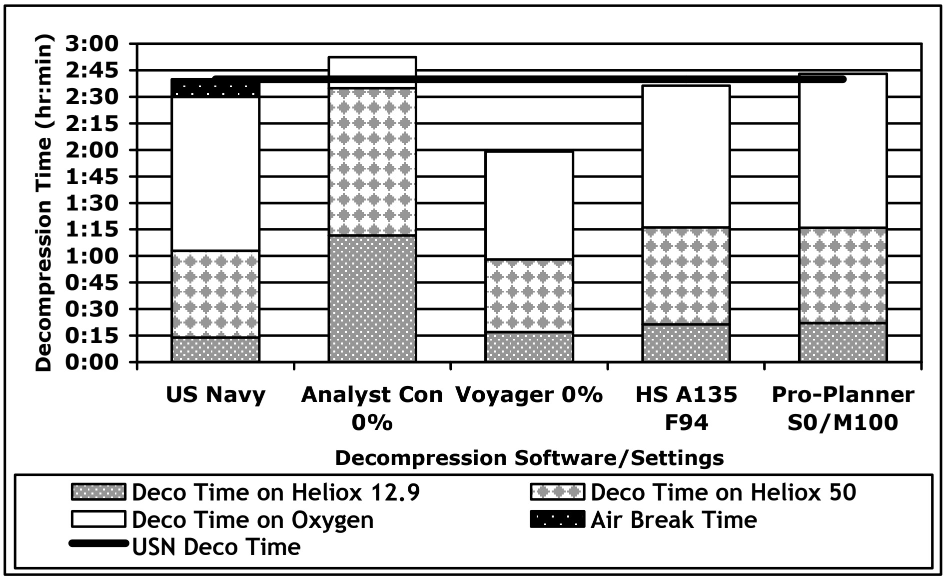

Figure 11. Decompression requirements for 300 fsw/20 min with adjusted dive computer simulations vs. US Navy heliox tables.

ations of the EMC-20H and VR3 computers met or exceeded the US Navy TDT. The NiTek and HS Explorer simulations showed at least 30 minutes less TDT (Fig. 10). When the HS Explorer was adjusted to its most conservative setting (A135 F94) it did not reach the US Navy TDT (Fig. 11), however if the same air break schedule were added it would reach the required TDT.

DCIEM Heliox Tables

The DCIEM Heliox Tables were validated with 1,471 manned exposures during their development. The tables state that the probability of decompression sickness is reduced to 2% in the normal range and 4% in the extreme exposure range. The 300 fsw/20 minute schedule is in the normal range (a bottom time of 30 minutes at 300 fsw enters the extreme exposure range). The DCIEM Heliox Tables use heliox 16/84 as the bottom mix (PpO_2 = 1.61 ata), switches to air at the first decompression stop (in the simulations air use was limited to 160 fsw), and a switch to oxygen at 30 fsw. Five minute air breaks are given for every 30 minutes of oxygen breathed and the last decompression stop is at 30 fsw.

None of the computer simulations reached or exceeded the DCIEM TDT requirement of 130 minutes. The range of the computer simulations was 64–109 minutes (Fig. 12). Adjusting the Analyst software to 25% conservatism and the Pro Planner safety factor to 15% produced TDTs equivalent to the DCIEM requirement while the HS Explorer at its most conservative setting (A135 F94) falls just 5 minutes short of the goal (Fig. 13). Once again, if the air breaks are added to the calculated decompression schedule, the HS Explorer would reach the table's TDT.

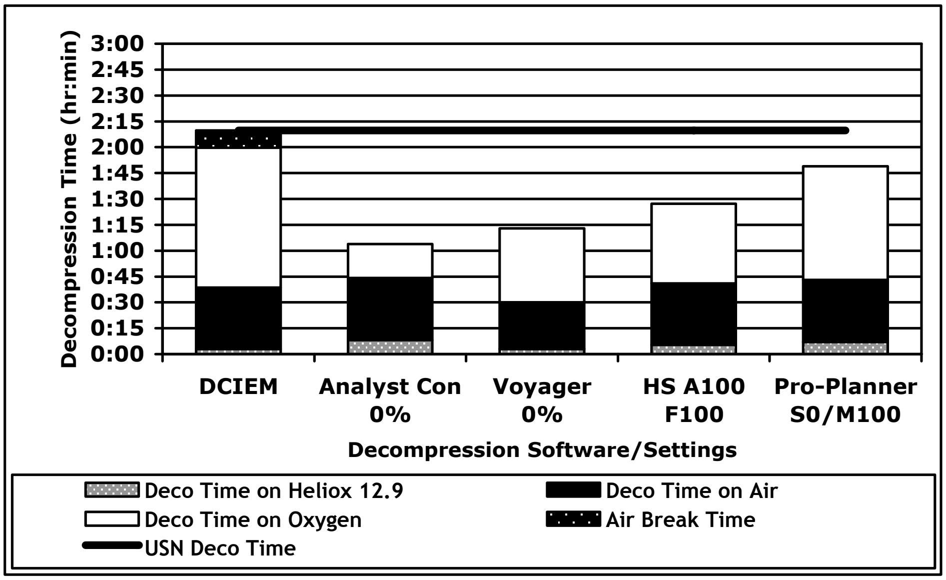

Figure 12. Decompression requirements for 300 fsw/20 min dive computer simulations vs. DCIEM heliox tables.

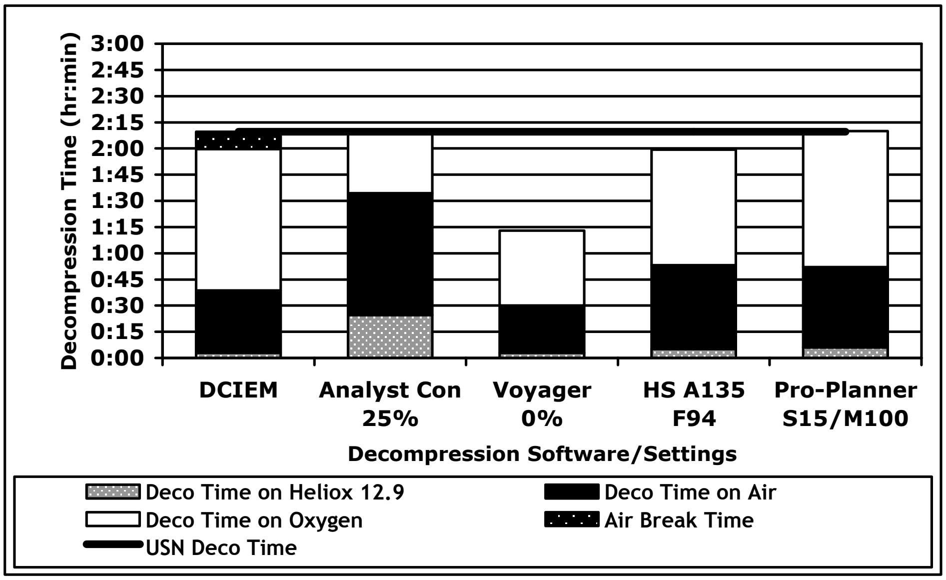

Figure 13. Decompression requirements for 300 fsw/20 min adjusted dive computer simulations vs. DCIEM heliox tables.

Table Comparison Issues

There were a few issues encountered in the simulations comparing the tables to the computer simulations:

- Only the Analyst and Voyager software packages allowed gases to be entered in fractions of a percent, so heliox 12.9 had to be entered as heliox 13 in Pro Planner and HS Explorer
- Pro Planner would not allow an entry of a gas which would exceed a PpO_2 of 1.60 ata. Therefore a depth of 297 fsw was used when the bottom mix was heliox 16

and the oxygen faction was adjusted to be as close to 1.6 ata as possible on decompression stops where the prescribed gas would have exceeded 1.6 ata.

- In the DCIEM simulation air is switched to at the first decompression stop. However, since some of the calculated stops were deeper than 200 fsw it was decided to set the air switch to 160 fsw, the deepest stop on the printed tables

Recalculating the Trimix Scenario

Based upon the comparisons of the computer simulations to established heliox tables, and the adjustments that needed to be made to achieve equivalent TDTs from software, the trimix dive scenario was recalculated using the levels of conservatism needed to meet the DCIEM table requirements. The Analyst software was set to 25% conservatism, the HS Explorer to A135 F94, and Pro Planner to a safety factor of 15%. Voyager was not adjusted. The resulting TDTs from the trimix simulation ranged from 110–146 minutes (Fig. 14). The increase in TDT was 52 minutes for Analyst, 35 minutes for HS Explorer, and 19 minutes for Pro Planner.

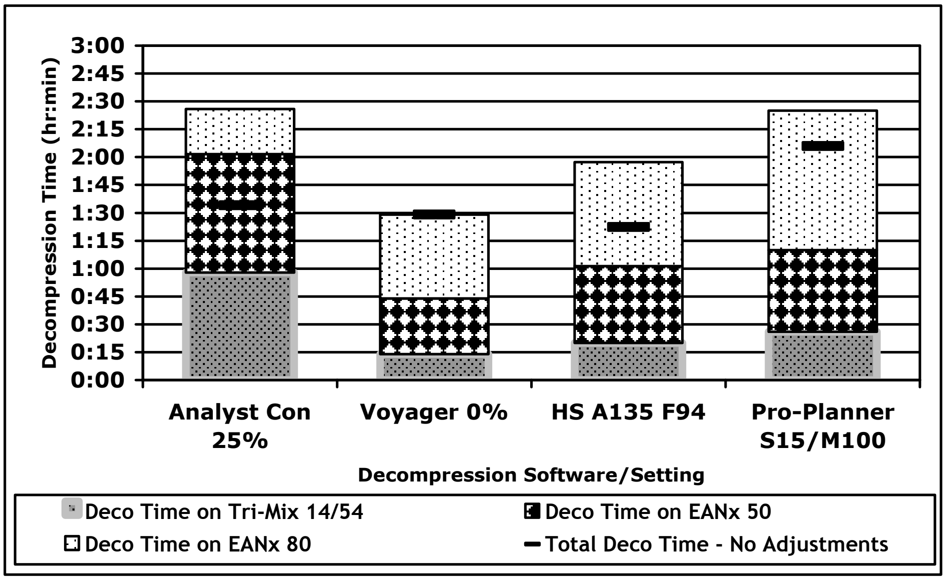

Figure 14. Decompression requirements for Trimix 14/54 300 fsw/20 min with adjusted dive computer simulations.

Simulations were also run with bottom times of 25 minutes and 30 minutes at these settings. The resulting TDT range for the 25 minute bottom time was 135–216 minutes and 178–291 minutes for the 30 minute bottom time. The addition of another five minutes to the bottom time resulted in 46 to 70 minutes of additional decompression time. For an additional ten minutes of bottom time 89 to 145 minutes of additional decompression time was required (Fig. 15).

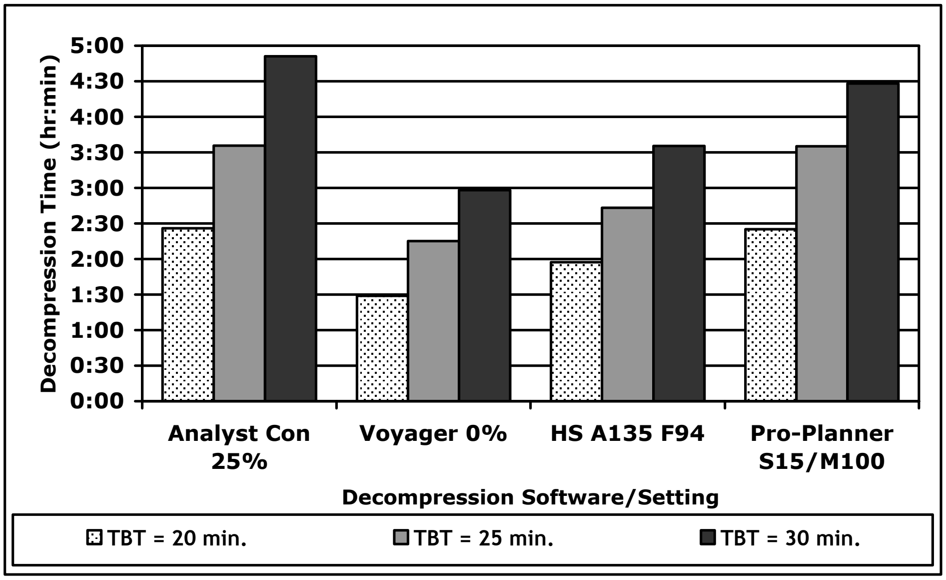

Figure 15. Decompression requirements for Trimix 14/54 300 fsw/20, 25, & 30 min with adjusted dive computer simulations.

Comments

As can be seen in these simulations, there are a plethora of possible decompression schedules available for a single 300 fsw/20 minute dive depending upon the decompression table or algorithm, any conservatism added to the algorithm, the composition of the bottom mix, and the decompression gases (composition and switch depth). The actual decompression schedule stops may vary greatly even though the same TDT is achieved. For example, the Analyst software tends to calculate most of the stops deeper and has shorter times with final decompression gas.

The main question is of the safety of the decompression scheduled generated by these computers, since there is little to no data available regarding their validity. Comparing them to established tables allows us to see if their schedules reach or exceed the table TDT requirement. Three of the four computers allow for adjustment to reach this mark. An obvious question that is raised in these comparisons is, “Why not use the established heliox tables and use computers as a back-up?”

A major concern in diving to these depths is the risk of fatal decompression sickness in the case of blow-ups from depth. Very serious consideration needs to be given to the Emergency Action Plan in case of a blow-up from depths as great as 300 fsw.

Recommendations

Based on the 300 fsw/20 min dives analyzed, the following recommendations are made for the currently available heliox/trimix dive computers:

- EMC-20H should be set to at least 25% conservatism.
- HS Explorer should be set to CF 9 (Asymmetric 135 / F=94).
- NiTek He not recommended (has no apparent algorithm adjustment).
- VR3 should be set to at least a Safety Factor of 15%.

- Dive computers may not be needed to control decompression for surface-supplied diving. Control of decompression can be handled by the surface-support personnel using established or “cut” tables.
- Dive computers still can be used to provide the diver with information on depth, time, and ascent rate, and be used as a backup to decompression tables.
- If dive computers are used, they can not be exposed to any gas filled environment in a decompression stage, way station, or decompression chamber.
- Bottom times for 300 fsw dives should be limited to 20 minutes.
- For heliox dives:
  - Surface support personnel with established tables control the diver’s decompression.
  - If a dive computer is used as a backup it should be able to be adjusted to require as much decompression time as the established tables – however, it will be difficult to find dive computers that can be adjusted to closely match the scheduled stops of US Navy or DCIEM decompression tables, even though the TDTs are the same.
- For trimix dives:
  - Decompression tables should be “cut” with a software program that will emulate the dive computer worn by the diver.
  - Surface-support personnel with these tables control decompression.
  - If a dive computer is used as a backup it should be adjusted to same level of conservatism as the “cut” tables.
  - Divers and scientific diving programs need to recognize that these trimix dive computers and software programs have not been validated with controlled studies.
  - Emergency protocols need to be established to be able to handle the possibility of diver blow-ups from depths that can potentially produce fatal decompression sickness

Conclusion

Scientific divers wishing to utilize surface-supplied heliox or trimix for diving to depths of 300 fsw need to be make decisions to either:

- Utilize established heliox decompression tables with the possibility of using dive computers as a backup.
- Cut heliox or trimix decompression tables using available decompression software packages with the possibility of using dive computers as a backup, or
- Use dive computers with heliox and trimix capabilities to control decompression.

If established tables are used then it will be difficult to closely match a dive computer to the decompression schedule of the tables.

If the dive computer or decompression software options are chosen then, in lieu of studies which have validated the decompression algorithm, the divers must have enough comfort and experience with the decompression algorithms and protocols they intend to use to be able to justify their use to their Diving Control Board.

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Addendum

At the workshop Karl Shreeves noted that he used the Dive Rite NiTek HE and that the decompression times calculated by the Voyager software seemed to be shorter than what he would expect for the NiTek HE. From his experience he has had better matching of decompression schedules with Abyss 120. He also noted that you could force the NiTek HE into more conservative calculations by setting it to a higher altitude range. However, when looking at the NiTek HE manual it does not say anything about manual altitude adjustment, instead it says the unit automatically adjusts to altitude changes.

The dive scenarios were recalculated using Abyss 120 to simulate the response of the NiTek HE dive computer and the results compared to Voyager calculations are presented in the table below:

Comparison of Voyager and Abyss 120 Decompression Requirements

		Decompression Time (hr:min)		
Scenario	Gas Mix / TDT	Voyager	Abyss 120	Table
Heliox 15.9 alone	Heliox 15.9 / TDT	12:32	11:21	---
Heliox 15.9 w/EANx 50	Heliox 15.9	00:28	00:23	---
	EANx 50	01:46	01:58	---
	TDT	02:14	02:21	---
Heliox 15.9 w/EANx 50 & EANx 80	Heliox 15.9	00:28	00:23	---
	EANx 50	00:24	00:37	---
	EANx 80	01:05	01:07	---
	TDT	01:57	02:07	---
Trimix 14/54 w/EANx 50 & EANx 80	Trimix 14/54	00:14	00:16	---
	EANx 50	00:30	00:30	---
	EANx 80	00:45	00:54	---
	TDT	01:29	01:40	---
US Navy Protocol	Heliox 12.9	00:17	00:15	00:14
	Heliox 50	00:41	00:39	00:49
	Oxygen	01:01	01:12	01:27
	Air Breaks	00:00	00:00	00:10
	TDT	01:59	02:06	02:40
DCIEM Protocol	Heliox 16	00:03	00:07	00:03
	Air	00:27	00:36	00:36
	Oxygen	00:43	01:05	01:21
	Air Breaks	00:00	00:00	00:10
	TDT	01:13	01:48	02:10

Using the Abyss 120 algorithm does extend the required decompression time compared to the Voyager software except in the heliox 15.9 only profile, where the decompression time was reduced by 1:11 minutes, but still was too long at 11:21. The only profile where the extension of the decompression time was greater than 15 minutes was the DCIEM protocol. The required decompression time for Abyss 120 was 35 minutes longer than Voyager, but still fell 22 minutes short of the DCIEM TDT. These results do not significantly change the outcome of the evaluation and, barring a technique to be able to adjust the NiTek HE's level of conservatism, do not indicate the need to modify the recommendations and conclusions presented in the main body of this paper.

SURVEY OF THERMAL PROTECTION STRATEGIES

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Introduction

The level of consideration given to diver thermal protection planning increases as water temperature drops below 25ºC (77ºF) and the duration of the dive increases. Additional planning is needed when the dive profile does not allow the diver immediate access to the surface, such as a significant decompression obligation. For example, a dive made to a depth of 90m (300 ft) with a bottom time of 30 minutes incurs over 4 hours of in-water decompression (*Table 14-3, the US Navy's Surface-Supplied Helium Oxygen Decompression Table*). This in-water decompression obligation can be shortened to 2 hours using surface decompression. However, in both of these scenarios the thermal stress loading takes place primarily during the in-water decompression portion of the dive when the diver is the least active and metabolic heat production is lowest.

In addition to surface decompression, there are other strategies for lowering or eliminating in-water decompression and subsequent thermal exposure. The only way to eliminate in-water decompression is by using a Class-I closed bell operated in either bell-bounce or saturation mode or a diver lockout submersible. The use of a closed bell or submersible allows the diver to return to a dry environment after completing the work portion of the dive, minimizing the thermal exposure. The use of a bell or submersible also allows for longer work periods on the bottom while minimizing the total thermal stress loading. However, Class-I bell or submersible diving operations require larger support vessels to facilitate the bell/submersible handling equipment.

For this paper the assumption is made that the proposed diving will be done with surface supplied equipment and utilizes a Class II open bell. The open bell functions as a diving stage and way station but does nothing to minimize the dive's thermal exposure. The Class II bell is commonly used in commercial diving at depths greater than 67 m (220 ft) or on dives with greater than two hours of in-water decompression (ADCI, 2004).

Planning Thermal Protection Needs

The first step in selecting the thermal protection strategy is to define the level of performance decrement that is acceptable at the end of the work portion of the dive and/or at the end of in-water decompression. Work done by Weinberger and Thalmann (1990) at the Naval Medical Research Institute (NMRI) broke diver performance into three functional categories based on the individual’s thermal state: fully functional, adequately functional, and barely functional. Table 1 provides the basic physiological parameters of these three categories.

Table 1.

Function Category	Core Temp 37 °C (98.6 °F)	Mean Skin Temp.
Fully	> 36.5 °C (97.7 °F)	> 29 °C (84.2 °F)
Adequately	> 36.0 °C (96.8 °F)	> 25 °C (*77 °F)
Barely	> 35.5 °C (95.5 °F)	> 20 °C (68 °F)

They went on to define the level of performance decrement that can be anticipated with each category.

- Fully Functional: **> 36.5 °C (97.7°F).** Little or no performance decrement due to thermal stress. Performance equal to 30 min dive conducted in warm water > 25 °C (77 °F).
- Adequately Functional: **> 36.0 °C (96.8°F).** Loss of mental performance and manual dexterity due to thermal stress, and may experience difficulty accomplishing mission tasks.
- Barely Functional: **> 35.5 °C (95.5°F).** Borderline for carrying out basic functions needed to maintain dive safety. This is the outside limit for exposure and is not intended for use in mission planning

When developing a dive plan, the planner should try to maintain the diver in the fully functional category. This is particularly important in the case of an untethered, free-swimming diver. The untethered diver needs to be fully functional to safely perform the dive and subsequent decompression. If the diver experiences the onset of hypothermia, and moves into the adequately functional category, the first skills to be impacted are the upper-level mental skills, such as the ability to do math and navigation. However, in the case of a surface-tended diver, decisions can be made at the surface and actions communicated to the diver and it may be acceptable to allow the diver to slip into the adequately functional category.

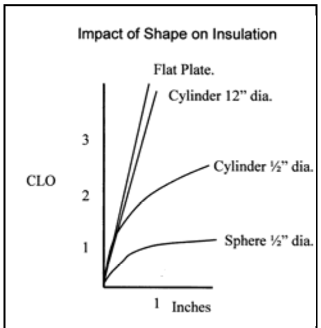


Figure 1.

In addition to the general thermal state of the diver, the hands and feet require special consideration as the water temperature drops below 7.2ºC (45ºF). This special consideration for the hands and feet is necessary because of the hemispherical geometry present on the tips of the fingers and toes, which limits the effectiveness of insulation (Nuckols, 1978; Beckman, 1996; van Dilla, 1957; Fig. 1). This in combination with reduced blood profusion to the extremities as the body experiences vasoconstriction in a response to cold. Without proper protection of the hands, finger temperatures will quickly drop to near ambient water temperature. In water temperatures below 12°C (53.6°F), the realm for Nonfreezing Cold Injuries (NFCI) is entered (Keating, 2000). NFCI is rarely mentioned or discussed in diving yet most individuals would recognize it by its more common name, "Trench Foot," commonly seen in cold-weather military operations. Thalmann (1987) reported divers experiencing NFCI involving the hands and feet following dives in water colder than 7.2ºC (45ºF). One case of NFCI involving the face was reported by Dr. P. Hamner who was conducting diving operations in the Antarctic Ocean (Stinton, 1978).

The following guidelines for hand/foot exposure limits were recommended in *Cold Water Exposure Guidelines for Passive Thermal Garments* (Thalmann, 1990) and augmented with information from Keatinge (2000) to ensure that divers do not develop Nonfreezing Cold Injuries (NFCI).

Hand and Foot Temperature Limits

- Fully Functional 18°C (64.4°F)
- Non Freezing Cold Injury Threshold < Week
- 12ºC (54ºF) approximately 3 hours (Keatinge, 2000)
- 8°C (46.4°F) for maximum of 30 min
- 6°C (42.8°F) immediate rewarming

The gray area for hands, feet and face protection is in the 12°C (53.6 °F) to 8°C (46.4°F) range is

- Individual Differences
  - Personal physiology
  - Previous thermal injuries
  - Acclimatization?
  - Equipment
- Nonfreezing Cold Injuries (NFCI).

Diver Thermal Protection Strategies

The two primary strategies used in minimizing thermal stress in diving fall into two categories: passive and active. Passive thermal protection reduces the rate of heat loss by surrounding the diver in a layer of insulation. The wetsuits and drysuits represent the two most common passive approaches in use. The active approach utilizes an external energy source to maintain the diver in thermal equilibrium or offset losses. The free-flooding hot water suit represents the most widely used active approach. Other active systems utilizing electric resistance heating (Neste, 2001) or liquid-heat transport garments (tube suits) are used in combination with passive garments (Crepeau, 1993; Nuckols, 2001). However, these latter systems are not typically commercially available.

Diver Passive Thermal Protection

The passive approach is broken into two sub groups: the wetsuits and drysuits. Both of these approaches derive their insulation primarily from trapping and stabilizing gas.

Wetsuit

The wetsuit is typically made with closed-cell foam neoprene rubber and derives its insulation from gas trapped within the cell structure of the foam. The concept of the wetsuits was put forward and developed by Dr. Hugh Bradner of Scripps Institution in 1951 (Hanauer, 2003). Dr. Bradner noted in his initial work that the closed cells in the rubber would compress with increased depth and would lose insulation. However, this was not seen initially as a major drawback, because the UDT swimmer would be operating at depths less than 10 m (30 ft) and swimming at 0.5 knots.

Beckman conducted a series of tests at NMRI to better understand the impact of depth on the effectiveness of the wetsuit (1964)

Table 2. Depth insulation units (clo)

Insulation With Depth	
Surface	.59 clo
33 ft (10m)	.34 clo
66 ft (20m)	.27 clo
99 ft (30m)	.22 clo
132 ft (40m)	.18 clo
165 ft (50m)	.15 clo

The clo units utilized in Table 2 are units of insulation similar to the more common R-value and are equal to $0.18/m^2 \cdot hr$ or transfers of $5.56\ kcal/°C \cdot hr$. Knowing the clo value of a garment gives the dive planner the means to estimate its effectiveness.

An additional factor not well understood about wetsuits is that the cell structure breaks down with repeated use. With the breakdown of the cell membranes, the cells flood and insulation value of the foam decreases. This breakdown was reported by Monji (1989) after studying the impact that compression and decompression cycles had on wetsuit insulation; however, his work did not address the mechanical impact wetsuits experience, which also breaks cell membranes down. This can be measured by simply weighing the suit after each dive. As the cells break down the suit holds more water and weight increases. The anecdotal comment here is that the diver always is impressed by the performance of their new wetsuit, not because the new wetsuit is that much better than the old suit when it was new, but that old wetsuit's performance deteriorated over time without the diver noticing it.

Even with these limitations the wetsuit continues to see wide use in shallow depths where it can provide durable and effective thermal protection for short-duration dives. However, the dive planner needs to understand its limitations when planning deeper and longer duration dives.

Drysuit

A drysuit, regardless of style, traps an envelope of gas (air being the most common gas) around the diver's body. Drysuits generally cover the diver's body, with the exception of the hands and feet, isolating the diver from the water. With additional suit accessories it is possible to totally isolate the diver from the environment. There are two primary construction styles used in fabricating drysuits. The first method utilizes the same closed-cell neoprene foam used in the construction of wetsuits and the second, shell drysuits are constructed using a wide variety of waterproof coated fabrics. The latter is becoming the more common style of drysuits. In both of these cases the suits are equipped with means for adding and venting gas during ascent and descent. Drysuits with valves are occasionally referred to as constant-volume suits or variable-volume suits, a hold over from when most of the drysuits used in the 50's did not have inlet and exhaust valve.

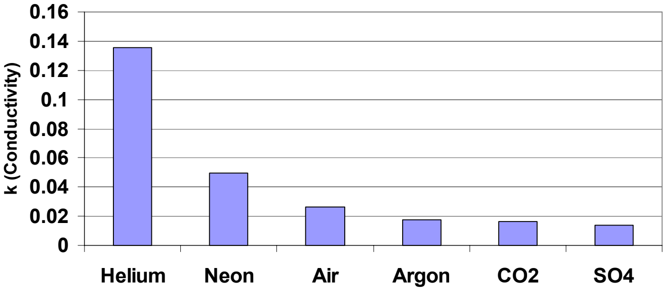
The total insulation in the foam-style drysuit is derived from the combination of the foam's insulation and the garments worn under the suit. The proportion of insulation from each layer is highly variable. Foam-constructed drysuits currently are offered in thicknesses ranging from 2-7 mm. The amount of insulation worn under the foam drysuit can range from a swim suit to the same insulated undergarment available for use with shell drysuits. In the foam-style drysuit, the insulation fraction provided by the foam decreases with depth just as it does with the wetsuit and the foam experiences the same damage with use as the wetsuit.

In the shell-type drysuit the total insulation primarily comes from the undergarments worn in conjunction with the suit. This allows divers using a shell-type drysuit to adjust the amount of insulation used to meet the anticipated exposure needs. Also, when alternate suit-inflation gases are used to increase the insulation value of the undergarments, the full benefit is available.

Drysuit Inflation Gas

Air has been the traditional drysuit inflation gas with some exceptions. In the past, when electric heating garments were used in combination with drysuits like the venerable Mark V or later during the 70's in saturation diving, the drysuits were inflated with heliox. The reason for use of heliox in saturation diving was that operators (COMEX in particular) did not want to introduce contaminants into the atmosphere of the saturation-chamber complex. The presence of helium has major impact on the performance of the suit because of its high conductivity (Table 3). Wattenberger (1978), in a series of thermal manikin tests done at ARIEN Natick facility, demonstrated that heliox in a shell drysuits would reduce the effective insulation of the suit ensemble by 71%.

Table 3. Gas conductivity.



The use of Argon as a suit-inflation gas has become very common in the technical diving community. Argon is used because its conductivity is less than that of air.

However, its value has been debated following tests done by Risberg and Hope (2001). The following bullet points outline how Risberg conducted the test:

- 26 Norwegian Navy Clearance Divers: age 21-33, mean wt 80.8 kg (2 dives each with 24 hr between dives) making a total of 52 dives
- Water temperature -1 ºC to 4 ºC (mean 2 ºC)
- Scuba with AGA full face mask
- 6.5 mm drysuit and woolly-bear undergarment
- Dives ~ 9 m for 60 min
- Divers did not know if they were using air or Argon
- Suit prepurged 3 times with Argon to ensure a high concentration in suit

During the dives the skin and core temperatures were monitored and the resulting data did not show any difference between air and Argon.

However, in a test done by Weinberger (1989) using CO_2 as the suit inflation gas, he reported a 52% improvement in suit insulation. Argon and CO_2 have conductivities that are comparatively close to air (Table 3). Why the great difference in test results? The different results can possibly be explained by the differences in the style of drysuits used. Risberg's tests utilized 6-mm foam drysuits and, as a result, a large fraction of the total insulation came from the foam. The addition of Argon would not change the intrinsic insulation of the foam and at 9m (29ft) of depth the foam contributes to a major portion of the total suit insulation. While in Weinberger's tests shell drysuits were used and the majority of the insulation came from the undergarments and, as a result, the CO_2 had a major influence on the outcome.

Hands

Optimum protection of the hands can be achieved with the use of dry gloves attached to the drysuit without wrist seal. The elimination of the wrist seal allows the free exchange of gas between the suits and glove (Fig. 2). The presence of a wrist seal can impede circulation of blood to the hand, which is already minimal when the hands are vasoconstricted. Work done by Thalmann (1987) and Stinton (1989) demonstrated that glove systems without wrist seals provided a higher level of protection for the hands. Thalmann reported that divers were able to rewarm the fingers by holding their hands over their heads and allowing the gas to inflate the glove/mitten to its fullest extent. In some cases with mitts the divers were able to draw their fingertips out of the mitt portion and rewarm them on their palms.

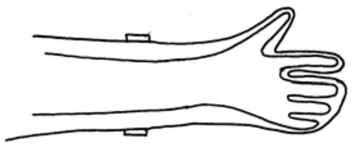


Figure 2.

Planning Thermal Exposure

Exposure planning has always been challenging for several reasons. The insulation values of passive garments are not well known and the tools to use them have not been widely distributed. Thalmann in *Cold Water Guidelines for Passive Thermal Garments (*1990) presented a simple algorithm to generate an exposure table. The algorithm can be set up on a Microsoft Excel spreadsheet and takes into account the following parameters: desired end of exposure functionality, water temperature, size of the diver, and the activity level. Table 4 was generated showing the levels of insulation needed to maintain a 75 kg (165 lb) diver fully functional in different water temperatures doing mild work. To use the table enter along the water temperature column then move across horizontally to the time in minutes that best meets the intended dive duration. From the time cell move up vertically to the clo value at the top of the column. The planner then can use a listing of clo values such as for different insulation packages and then determine a layering system most suitable for the planned dive. The challenge to the planner as the water temperature drops below 7ºC (45ºF) is protection for the hands and toes.

Table 4. Insulation requirements for a 75 kg diver.

Water Temperature		**Insulation in Clo**									
°F	**°C**	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2
77	25	92	165	▨	▨	▨	▨	▨	▨	▨	▨
68	20	20	67	352	▨	▨	▨	▨	▨	▨	▨
59	15	**NR***	29	61	145	720	▨	▨	▨	▨	▨
50	10	**NR***	18	34	59	108	239	720	▨	▨	▨
46	8	**NR***	**NR***	29	48	80	146	352	▨	▨	▨
Below this line exposure limit may be controlled by fingers and toes											
43	6	**NR***	**NR***	25	40	64	105	194	352	▨	▨
39	4	**NR***	**NR***	22	34	53	82	134	720	▨	▨
36	2	**NR***	**NR***	20	30	45	67	103	137	560	▨
32	0	**NR***	**NR***	**NR***	27	39	57	83	216	493	▨
28	-2	**NR***	**NR***	**NR***	24	35	49	70	156	274	▨

NR* Not Recommended inadequate protection

▨ Level of protection may be too high

In addition to the work done by Thalmann on exposure planning, Bradner (1985) compiled an exposure guideline (Table 5) for dive planning for COMNAVSPECWARGRU ONE. Bradner's guidelines included means for planning long duration dives using both wetsuits and drysuits.

Table 5. Exposure guidelines.

Dry Suit Under Garment Type	Clo (Air)
Polypropylene Underwear Medium wt.	0.1
Single Layer Fleece (200 gm/m^2)	0.3
Thinsulate 200 gm/m^2 Type B	0.6

Thinsulate 400 gm/m^2 Type B	1.3

Diver Active Thermal Protection

Free-Flooding Hot Water Suit

The free-flooding hot water suit (Fig. 3) works by surrounding the diver in a thermally neutral envelope of water 92-94 ºF (33-34 ºC). This envelope of water is maintained by means of continuous flow of water from the surface. Sea water or fresh water is supplied to a heater and/or heat exchanger at a rate between 2-8 gpm (7.5-30 lpm), is heated and then pumped down to the diver via an umbilical. The hot water suit is made with 5-6 mm closed-cell neoprene foam, the same as used in a wetsuit. The suit is equipped with a manifold and water distribution tubing for distributing and maintaining a layer of water around the diver's body. The manifold is also equipped with a bypass that allows the water to be diverted from the suits when the diver is entering or exiting the water or in the event water temperature control is lost. The suit is designed to fit very loosely to ensure water circulation around the diver's body. Water is continuously being discharged from the suits by way of the front zipper and junctions between the boots and gloves and around the neck.

Figure 3a.

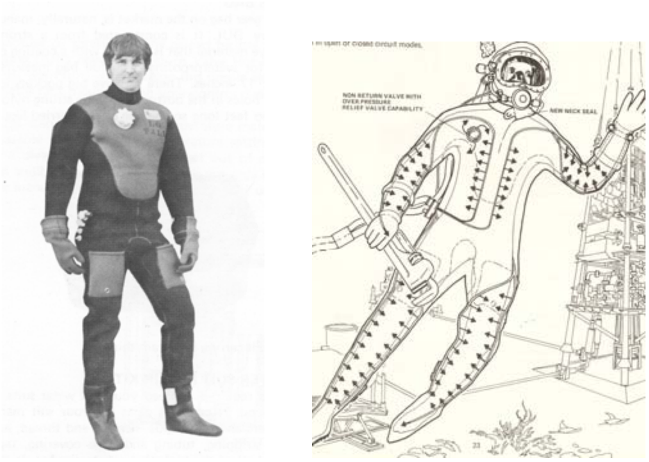


Figure 3b.

Other variants of the hot water suit have been built but their use has not seen wide acceptance in the commercial offshore industry, the primary user. The basic configuration was adopted and a proven track record of performance and durability were established, obviating the need for change. Currently there are four manufacturers of hot water suits worldwide and all the models are conceptually the same.

Specialized models of hot water suits have been built such as the NRV (Fig. 3), which is a closed design for use in special applications including diving in hazardous environments (Stinton, 2003). In addition to the NRV variant, closer fitting suits made with lighter materials have been built and used in applications requiring greater swimmability.

Table 6. Advantages and disadvantages of hot water suits.

Pros	Cons

• Long history of operational experience
• Robust
• Simple diver training
• Operate over wide temperature range without changes to the diver's equipment configuration
• Hands and feet are not impacted by lower temperature water
• Can be used in environments where the diver needs to be cooled
	• Topside support
	• Larger diameter umbilical for hot water supply
	• System Maintenance
	  • Suits
	  • Umbilical
	  • Heater

Conclusion

The use of free-flooding hot water suits provides a robust and simple approach that can be used over a wide range of water temperatures for long duration dives. In addition, variations in water temperature, depth, or duration have no impact on the diver-carried equipment. The system simply adapts to these changes with adjustments made on the surface to the hot water heaters' output temperature and/or flow rate.

This allows diver training to be focused on a single equipment configuration with no regards to water temperature, planned depth, or duration. The hot-water approach can also maintain the diver in the fully functional category without regards to water temperature, depth, or duration of the dive. The approach also provides the diver a high level of dexterity as glove types are easily adjusted as needs dictate. The approach is simple when compared to the passive approaches where one must determine the level of protection for the diver and their hands based on the anticipated exposure.

When topside support and deck space is limited, and/or the diver is untethered, the use of wetsuits or drysuits are the two alternatives. However, with these passive approaches the level of planning increases as the water temperature drops and the dive depth and duration increase. The dive planner needs to be provided with planning tools to develop a diver thermal exposure management plan. These tools can be developed from the work of Thalmann (1990) and Bradner (1985).

The wetsuit provides a simple and robust approach in water temperatures of around 25ºC (77ºF) and above. A high quality 6-7 mm wetsuit can provide more than 3 hours of exposure protection in this temperature range. The use of a wetsuit minimizes diver training and reduces topside support needs. However, the dive planner has to consider the temperature range for the complete profile of the dive. In addition, the limited operational range of the wetsuit needs to be fully understood by the planner.

When the exposure limits of the wetsuit are reached and the water temperature drops below 25ºC (77ºF), a drysuit with appropriate insulation and accessories can greatly extend the exposure range. As water temperature drops below 7.2ºC (45ºF), additional consideration needs to be given to the hands and feet to prevent NFCI. To protect the hands, a dry glove system is needed and ideally the glove system should not include a wrist seal. The feet will also need to be protected by additional insulation.

On dives with duration greater than one hour, the drysuit should be configured with a urine elimination system. In the technical diving community, the drysuit is typically equipped with an overboard dump system that utilizes an external catheter. However, this system is only available for male divers and the alternative to the overboard dump is an adult diaper.

Argon, as an alternate drysuit inflation gas, can extend the operational range of a drysuit system. Argon has a long history of use with recreational divers, working divers, and exploration groups. The Wakulla Karst Plains Project (WKPP) is exploring, mapping, and setting up hydrology monitoring stations in the cave systems of northern Florida. The WKPP is conducting dives to depths of over 91 m (300 ft) in 21ºC (70ºF) water with bottom times in excess of 5 hours and decompression times approaching 20 hours. The WKPP uses Argon as a suit inflation gas on all dives. In addition to the WKPP, the European EKPP project has been conducting dives with similar depths and durations but in colder 11ºC (52ºF) water. EKKP is also using Argon as the suit inflation gas (Jablonski, 2005).

Drysuits require a higher level of diver training and maintenance than the wetsuit or hot water suit. However, a well-trained and properly-equipped drysuit diver can carry out long duration dives over wide range of temperatures.

A first consideration in selecting the type of diver thermal protection is the range of temperatures, depths and anticipated durations. This, coupled with the size of the surface support platform, will dictate the type of equipment that can be accommodated and the methods that can be used to minimize the diver's thermal exposure. The resulting thermal exposure management plan should always keep the divers at a level of full functionality; which gives the diver some leeway in the event of unanticipated problems.

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2. Decompression/Physiology Discussion Session

G.Egstrom: On your graphs, were those outliers at the far end in the 300-foot range? I know you had some data points that were down within the very low border, and then the line would go way up and there'd be one datum point.

W.Gerth: Bottom line is no, they're not outliers. We're getting into some issues here regarding the state of the art of our modeling capability. I could go on for hours about that. If I were to show you the estimated risks of the exceptional exposure schedules in those spots, you would see the risk rapidly going up to 60, 70, 90% with this model. This model is not a strict bubble bind model. This DCS risk is not a function of model bubble volume compartments. We do have such a model in development that does a lot better on the higher risk dives under the LEM model. The reason for the difference is that the LEM model handles oxygen as it contributes to DCS risk in a way much different than the bubble volume models that we now have. The way LEM handles it is kind of a rubber band approach whereas our bubble volume models actually incorporate the helium/oxygen saturation curve and lets oxygen exchange with tissues as bubbles grow in the tissues according to that curve. LEM doesn't. So, we have better technology. This technology works well up to PO_2s in the order of 1.7. Higher than that, which you do get in some surface-supplied dives, it starts over striving a risk of DCS from oxygen, something that doesn't happen in the bubble volume model. A long-winded answer to your question.

JP. Imbert: In the revised table, do you still carry the option of the switch to pure oxygen at 50 feet?

W.Gerth: No.

JP. Imbert: You dropped that one? Replaced by?

W. Gerth: I'm not imminently familiar with the emergency procedures. You say do we have the option? Operationally no. One of the main objectives was to get rid of the 50- and 40-foot oxygen breathing.

JP.Imbert: How do you exactly define your decompression stress, and how is it related it to the symptoms?

C.Gutvik: Currently we just use the total volume of excess gas as a measure of decompression stress. We have the ability to weigh this between different tissues. We can say that bubble growth in the muscle is worse than getting bubbles in the fat tissue for instance because it's most likely that bubbles growing in muscles are more likely dislodged from the endothelial layer and then are washed over to the arterial side. But bubbles don't grow in the fat tissue, they just stick there and do not cause serious problems.

K.Shreeves: Do you recall what setting you had Voyager on when you did your analysis, the conservatism setting?

K.Huggins: That was set at zero because I didn't see anything in the software that stated that there was any level of conservatism over the Bühlmann model.

K.Shreeves: The reason I ask is I've got quite a number of dives on the NiTek Aegis and what you presented wasn't lining up with my experience. I find that the algorithm of the Abyss 120, which is more conservative than Voyager set at zero, lines up more with the NiTek Aegis., which in my experience, is more conservative than Bill Hamilton's DCAP program. For those who are evaluating computers, you might get a different result than what Voyager gave. That was certainly a good basis for it, but we probably needed the conservatism.

K.Huggins: It would have been nice to have it.

K.Shreeves: I'm surprised Lamar Hires didn't get back to you on that. You actually can raise the conservatism in the NiTek Aegis. It's a bit of a workaround, but you can go to the altitude mode and select an artificially high altitude, which will raise its conservatism.

A.Brubakk: Regarding the use of computers in trimix diving, the point is that if we talk about dive computers actually attached to the diver, they're probably right. However, if the algorithm is reasonably right, a topside computer would give you much more flexibility. For a surface-supplied diver, you have all the computing power that you need if you move the dive computer from the arm of the diver to the surface. I agree with the fact that no one has actually evaluated these procedures, which is a serious drawback. On the other hand, the validation of the dive tables, particularly in the deeper range, is also not very impressive. I am, therefore, not sure if tables actually are much safer.

M.Lang: You're referring to the US Navy tables?

A.Brubakk: Any tables. Listen to what was said earlier today, there is very little experience with deep trimix and mixed-gas diving and the experience that we have indicates that the number of decompression incidents is pretty high.

M.Lang: Now I'm very interested to hear of the commercial diving operational experience. Many of the commercial tables are proprietary and have been tweaked, to meet their specific objectives, but certainly as far as experience level and number of dives in the 300-foot range, it's got to be tremendous, right?

G.Beyerstein: Literally thousands, even to the 300-foot level and not by analyzing on the dive computer. The DCIEM tables are good tables. It needs to be remembered that Ron Nishi made that choice not to use 50/50 nitrox for logistical reasons because their diving vessels had no room for 50/50. Otherwise, he would've used it. The Navy is another matter altogether. We've heard several discussions about risk here and speaking now as a safety manager for the last 20 years, conventional wisdom is that risk is a combination of two factors: the likelihood of something happening (from statistical analysis) and the consequences of that happening. In order to properly evaluate risk, you have to take both of those into consideration. The consequences of something happening are twofold. In our business a DCS bend, for instance, we can treat if you have a chamber and the ability to treat on site. There is another consequence that has assumed orders of magnitude more importance in the last few years, the cultural emphasis. Glen Egstrom stated zero risk not being something that we could achieve and yet in our business, that's our aim. It has become intolerable to hurt anybody to any degree now. One bend with unresolved serious symptom equals one lawsuit equals two to three million dollars. It depends on what level of risk, what level of consequence that you can accept in the scientific community. When I hear the military people talking about two to four percent DCS, that to me is abhorrent. If any commercial company tried to function in that realm, they'd be out of business in an instant, whereas the military can accept that risk. They have a mission and can tolerate that level. Any attempt to transpose military experience to commercial or even scientific experience is fraught with difficulty and certainly should be considered very carefully.

M.Lang: In the science community's attempt to implement a new 300-foot seawater mixed gas program, one major incident or fatality will shelve the effort for the next 50 years.

W.Gerth: The issue of two to four percent, as I had tried to stress and Mike Gernhardt re-emphasized, those are risks of schedules in the tables dived as written. If you look at the actual incidents of DCS in the U.S. Navy diving operations, overall that's really very low.

M.Lang: You're talking about the outer envelope of the square-wave profile's shell, right?

G.Beyerstein: The actual lab quality tests that produce those kind of numbers don't live in the real world. It's true that we don't dive square profile dives, but when you get sheer volumes of numbers of decompression dives over a long period of time, then you have data to consider. Rather than talk about percent, we usually prefer to talk about the number of undeserved bends hits. If you have a bend where the dive profile is right, without table compromise, and no succession of susceptibility factors all occurring at once, we call that an undeserved bend. On standard air tables that are modified in commercial situations, we get maybe one bend in 1,500 dives. On the final iteration of the SubSea tables after they were changed we had over 4,000 decompression dives. Probably triple Zs with only one suspected case of bends. Since then other companies have been pirating and using them we're getting even more experience, whereas on gas, maybe one bend in 800 dives is as good as you're going to get.

M.Lang: Jack Reedy mentioned 'acceptable standard of practice' for a community when he summarized the commercial diving section of the repetitive diving workshop in 1991. For the commercial, military, scientific, and recreational diving communities, that is different, almost by orders of magnitude. The data published at the time was one DCS hit per 1,000 dives for the commercial diving community. That rate reflects the severity of dive exposure and the type of diving performed, but more important is their risk mitigation. As does the military community, the commercial divers have technicians and chambers on site, which the recreational and scientific diving communities do not. There are thus different levels of acceptance of risk for a particular communities, and it remains important to distinguish them when you're comparing incident rates because of the nature of the activity and very different exposures.

P.Ruden: The Navy experienced difficulties on the TWA Flight 800 dives that they attributed to decompression sickness as a result of using hot water suits. Was there a definitive conclusion on that issue?

J.Wilkins: I was at the Experimental Diving Unit at the time the TWA Flight 800 dives were happening. We were looking at that long and hard to try and figure out exactly what was going on. We experienced a higher degree of decompression sickness than we thought we were going to, even when we substantially jumped tables and still were having difficulties. We subsequently dug into the thermal effects associated with decompression sickness. I didn't see much opportunity to insert the thermal effects into the decompression models, whether you're talking a gas content model or a bubble volume model. We have reason to believe that thermal influence is a substantial factor. We ran some warm/warm, cold/cold, warm/cold, cold/warm dives at the EDU anticipating that we'd find what everybody suspects and intuitively knows that one approach is better than another. Over hundreds of dives we found a substantial difference, a surprisingly high correlation of the fact that by keeping the diver cold on the bottom and warm during decompression the incidence of bends was greatly reduced. We're trying to make a final determination of which decompression model is the way of the future. We want to find a model that also ultimately allows for thermal contribution if you just measure skin temperature. We found in the most recent series of tests thermal contribution to be a substantial input as to whether or not the bends incidence increased or decreased. We're also looking at long duration SEAL opportunities and swimmer delivery vehicles, where the hands and feet drive the divers out of the water. Dale High at NEDU has gone to a great lengths to actually map the thermal mass of the hand, where it loses heat, where you can apply heat, and how much heat you need to apply over what schedule so that you can actually schedule the energy application to the hand in an active heating element manner. You can then drop the energy requirements down to something that's manageable, batteries that are the size and about the same density as lead that could be used for weight belts on or around the body, a double contribution. We're working with a couple of manufacturers to take a look at some materials that can apply the heat as mapped against the human hand and are hoping that we're on the edge of a breakthrough here for hands, and then ultimately, feet

D.Southerland: There were several things that went on during TWA 800 dives. Several factors were changed throughout the dive. People suspected difficulties were due to thermal problems or changes in thermal status of the diver on the bottom during decompression. Changes were made to what they were wearing, but also to the bottom time. This raised the questions that resulted in the studies at EDU. Leffler, a Diving Medical Officer there published those studies.

W.Gerth: Exercise affects decompression, and thermal factors are equally, if not more, important. You have to keep in mind where the heat or cold is being applied to the diver. In the TWA cases, and the dives looked at by Tom Shields for the HSE, he made a similar conclusion that was reached in the TWA 800 dives, and that was that use of a hot water suit increased DCS incidents. This is consistent with the other information we've gotten from experimental studies. Going to a hot water suit will get you warmer on the bottom, but all these dives were sur-D-O_2. Whether you were cold or warm on the bottom, they were going to sur-D-O_2 under equivalent conditions. The difference between the higher DCS and the lower DCS cases discussed had to do with just going warm on the bottom.

P.Ruden: I remember conducting diving operations out of San Francisco, surface-supplied, mixed gas, 240-260 feet from open bells off the ASR9 using a band mask and hot water suits. We spent two and a half weeks diving every day, all day long, working hard under heavy sea conditions. We never bent anybody and did sur-D-O_2 for all the dives.

D.Long: In the 1970s when they first started opening up the gas fields off of Great Yarmouth, Taylor Diving was out there trying to lay a pipeline. They couldn't keep a guy on the bottom in a wet suit more than about 20 minutes, and he couldn't talk when he came up. They were doing in-water decompression followed by a surface decompression. The guys were so cold they were afraid they were going to die during the in-water decompression, so they started pulling them out and it actually got to the point where they were skipping two decompression stops, pulling them out, putting them in surface decompression and the guys decompressed fine. They said our tables are off, they could do that. They got to the point where it was not possible to do the job and finally brought hot water suits up there. As soon as they put hot water suits on the divers, they went to the same decompression profile of missing the two stops and bent many of them. The report came back that hot water suits give guys the bends, but they're a lot more comfortable. Thermal factor is every bit an issue with the diffusion of gas, as is the gas mixture itself, and related to the level of work. The harder he works, the more gas he takes on. We have seen cases where with a thermal component, whether it be hot water or surface decompression, the body changes such as when guys get inside of a chamber up against the cold wall. If we keep that diver in good thermal condition all the way through the cycle, we're going to be okay.

A.Brubakk: This all boils down to the fact that perfusion places a significant role in what's going to happen. You have to have a prescription for the decompression that takes into account that perfusion is different, and you have to adjust your decompression requirements accordingly. That's the temperature, the exercise, and at what time in the cycle it is applied. In the North Sea, deep bounce dives are hardly ever done. The reason for this is that all procedures as were shown by several studies, have had a too high incidence of decompression sickness. We need to do something radical about the procedures if we're going to use bounce dives using trimix or heliox. You probably should not do these dives, at least not until we have much better procedures, without having a chamber on site so you can treat problems. You probably can't do it with the level of safety that you want to have in the scientific diving community without some kind of treatment capability.

B.Stinton: Around 300 feet respiratory heat loss is about 25 percent of metabolic heat production, so we can put somebody in a hot water suit and keep their skin in a thermally neutral environment. The cooling is taking place directly out of the core of the body. Go to 300 meters and keep somebody in an electric suit and then watch them breath 40 degree hyperbaric helium and they're shivering within minutes. The fact is we can keep the skin at perfect temperature, but if we don't protect the respiratory channel through gas heating, then possibly that's where we're getting some problems. If you take nitrogen-specific heat and density it is worse, therefore nitrox is has a high heat loss. Trimix is higher than heliox so we need to look at that fact because at 300 feet we're basically at 25 percent of metabolic heat production as respiratory heat loss and at 600 feet it's about 50 percent. If you work more and do generate more heat, you're just losing more because you have to breathe more. That has to be taken into consideration.

K.Kohanowich: Exercise has a significant effect on incidents of decompression sickness. Have any recommendations come out of that work?

M.Gernhardt: With respect to our altitude decompression, we have a validated procedure that is being used on the space station now. That involves exercise during oxygen pre-breathe prior to decompression. From the commercial diving background on our multilevel dives that we did, I don't remember any DCS incidents in 30,000 dives per year. There's also research that shows that exercise after decompression actually increases the decompression stress. There's some confounding effects, but the indication from our laboratory research in the altitude case and the commercial diving experience is that exercise with relatively low levels of supersaturation is actually a good countermeasure for decompression stress.

A.Brubakk: This is so complicated. We have data from experimental air dives that shows that actually exercises after the decompression, even when they had a considerable number of gas bubbles, reduced the amount of gas bubbles. It is complicated. The whole thing we learn from all of this is that these relationships are not simple.

K.Huggins: Both Vann and Jankowski published studies looking at mild exercise during decompression that reduced stress.

MEDICAL FITNESS AT 300 FSW

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Introduction

The American Academy of Underwater Sciences currently allows diving to 190 feet of seawater (fsw) (58.2 meters of seawater (msw)) and would like to extend that operating depth to 300 fsw (91.9 msw) for bounce (*i.e.*, non-saturation) dives. This paper discusses additional medical requirements to allow divers to work down to depths of 300 fsw and will not discuss saturation diving medical standards. It is beyond the scope of this paper to compare general diving medical standards for different organizations. Rather, this paper will describe the additional medical requirements of selected organizations that allow divers to dive deeper than the current AAUS compressed-air scuba limit of 190 fsw.

Throughout the world, organizations using divers almost universally require that those divers meet some sort of minimum medical standards for diving. Generally, the medical standards are based on the underwater environment, hazards of the job itself (irrespective of the underwater component), and the degree of litigative promiscuity of the society in which the organization operates. The diver will undergo periodic medical examinations by a physician with some degree of knowledge in diving medicine who will use the organization's medical standards, along with the physician's knowledge/experience to determine the fitness of the diver to perform his/her duties underwater. Generally, the physician has great leeway in making a determination about the diver's medical fitness to dive.

Organizations Considered

Several organizations that allow diving deeper than 190 fsw were identified in the commercial, military, and other governmental sectors. The selection of specific organizations was based on the author's familiarity with the organizations and the ready access of information by web searches, e-mail, or telephone calls. There are other good organizations, but the author felt that the organizations finally selected would provide sufficient representation of the sectors from which they were drawn to provide an adequate view of diving medical standards in general.

These included (in alphabetical order within each sector):

Commercial

- Association of Diving Contractors International (ADCI)
- The International Marine Contractors Association (IMCA)

Military

- Canada
- North Atlantic Treaty Organization (NATO)
- United Kingdom (UK)
- United States of America (USA)

Other Government Agencies

- Health Safety Executive (HSE)
- National Oceanographic and Atmospheric Administration (NOAA)

In addition, the American Academy of Underwater Sciences (AAUS) medical standards were also considered since the AAUS is standard-setting body for scientific diving.

Findings

The medical requirements for diving were examined for all of the organizations mentioned earlier by examining pertinent printed documentation and web pages along with personal communication with knowledgeable individuals.

AAUS

The AAUS[1] medical standards require age-based periodic examinations by a physician of the diver's choice. The physician does not have to be trained in diving medicine, although it is preferred that a physician be selected who is so trained. Specific laboratory tests are required, and the physician may order additional tests as deemed necessary. Divers must pass the diving medical examination and be certified by the physician as medically fit to participate in scuba diving.

The AAUS standards allow diving deeper than 190 fsw using mixed gas. There are no additional medical requirements mentioned in the AAUS standards for such diving. It is interesting to note that the AAUS standards restrict surface-supplied diving to a maximum depth of 190 fsw. Therefore, under the current AAUS standards, any mixed gas diving deeper than 190 fsw must be performed on open-circuit scuba or rebreathers.

Military

Canada

Currently Canadian Defence forces do not have additional medical requirements for bounce dives deeper than 190 fsw[2]. However, Canadian Forces medical instructions are under review and a major change to the medical requirements is being recommended to the senior medical policy makers and is expected to be approved this year[3]. Under the new instructions, divers will be divided into two groups -- shallow water (dive depths less than 15 msw (49 fsw)), and deep water divers (may dive deeper than 15 msw). Deep water divers will include Clearance Divers. Deep water diving candidates will be required to undergo a workup for patent foramen ovale (PFO). Candidates with a PFO larger than 9 mm diameter will be disqualified from deep water diving, but may continue as a shallow water diver. As a grandfather clause, all current Clearance Divers will be offered the PFO workup and corrective surgery if the results would be disqualifying. The workup is voluntary unless the diver has an episode of severe decompression sickness.

NATO

The NATO fitness to dive standards (ADivP-2)[4] do not mention any medical requirements based on depth. However, ADivP-2 is an early attempt to document a consensus about diving medical standards among physicians from multiple countries. Therefore, although ADivP-2 contains general acceptance/rejection guidance for diving, it often defers to the diver's national standards for specifics. For example, ADivP-2 mentions neither the periodicity of the diving medical evaluations nor the specific laboratory tests required as part of the examination.

UK

The Royal Navy has diving medical requirements[5] for three types of diving: Service Occupational Diver, Acquaint Diver, and Military Recreational Diver. Since only the Service Occupational Diver performs occupational work underwater, its diving medical standards will be examined in this paper.

There are no additional diving medical standards for the Service Occupational Diver based on depths with the exception of screening for dysbaric osteonecrosis. All Clearance Divers are required to have a full long bone radiological survey upon completion of initial training and on leaving the Service. In addition, divers who dive to depths deeper than 50 msw at least ten times per year should have additional full surveys performed no more frequently than every five years.

USN

The U.S. Navy does not have any additional medical requirements for bounce diving to 300 fsw vice 190 fsw. Change 126 of the Manual of the Medical Department[6] did separate Naval Special Warfare (NSW) and other Special Operations (SO) medical standards (Article 15-105) from the “regular” Navy diver standards (Article 15-102). However, that change was made to allow consideration of the additional hazards (such as parachuting) other than diving that the NSW and SO personnel face.

Other Government

HSE

The HSE and local government are the enforcing authorities for the Health and Safety Commission which is responsible for health and safety regulation in Great Britain[7]. HSE's Diving Group exists to reduce fatalities and major accidents across all sectors of the diving industry, not just offshore diving[8,9]. The HSE Diving Group responsibility covers all types of commercial diving including, but not limited to, scuba, mixed-gas, and saturation diving.

The HSE does not currently (as of May 2005) have additional medical requirements for divers performing bounce dives deeper than 190 fsw[10]. However, wording in the document referenced generally "recommends", not "requires" specific standards. In addition, the HSE relies heavily on the recommendation of an Approved Medical Examiner of Divers (AMED), who must examine the diver and has great latitude in the diver's evaluation. Based on the results of the medical evaluation, the AMED may place restrictions on the type of diving in which a diver may function.

NOAA

NOAA is a U.S. federal agency that focuses on the condition of the seas and atmosphere. It is administered by the U.S. Department of Commerce[11]. The diving related functions of NOAA involve diving that include scuba with air or nitrox, mixed-gas, and saturation diving.

NOAA does not have additional medical requirements for diving deeper than 190 fsw[12]. However, they do perform cardiac stress testing on any diver who conducts decompression stop diving[13].

Commercial

ADCI

The ADCI was founded in 1968 to promote standardization of commercial diving practices. Currently the organization has over 500 members in 41 countries, although most companies are US-based[14]. Diving performed by ADCI members includes, but is not limited to, scuba, mixed-gas, and saturation diving.

The ADCI does not have additional medical requirements for diving deeper than 190 fsw[15]. However, the examining physician will make recommendations based on diver's examination and review of the essential job functions that the examined diver will perform. The ADCI recommends, but does not require, that the examining physician be trained or experienced in diving medicine for commercial divers. If the examining physician lacks diving medicine knowledge/training, then the examining physician should consult with another physician who is qualified, but that step is also not required.

IMCA

IMCA is also an international trade association of commercial companies with a focus on standardizing commercial diving practices. It was formed in 1995 with the merger of two other organizations, the AODC (originally founded in 1972), and DPVOA (founded in 1990). IMCA had over 250 organizations in early 2004[16]. The membership is worldwide, but most companies are northern European-based. Diving performed by IMCA members includes, but is not limited to, scuba, mixed-gas, and saturation diving.

IMCA International Code of Practice for Offshore Diving (IMCA D 014) requires each diver to obtain a certificate of medical fitness to dive from a physician trained in diving medicine. Until 2001, IMCA relied on the HSE to provide a list of suitable trained physicians. Afterwards, IMCA released an information note (IMCA D 20/01)[17] to help members identify appropriated qualified physicians, and also gave key elements in the medical examination, based on the HSE requirements. Today, IMCA recognizes physicians trained in accordance with "Approval of Diving Medicine Courses"[18], a publication produced in January 2006 by an alliance between the Diving Medical Advisory Committee (DMAC) and the Medical Subcommittee of the European Diving Technology Committee (EDTC).

The author, a non-member, had no ready access to IMCA D 20/01. However, since IMCA has a close relationship with EDTC and sells the printed version of EDTC's publication "Fitness to Dive Standards", the author used the EDTC publication as IMCA's diving medical standards guidance. A freely downloadable, electronic version of the document is available at the EDTC web site[19].

The EDTC publication stresses the importance of having a qualified physician perform the diving medical evaluation, rather than the use of pass-fail checklists. Such a qualified physician is necessary to judge medical fitness by taking into account the diver's job description and the worksite's environment conditions.

The EDTC recommends no specific additional diving medical standards based on depths with the exception of screening for dysbaric osteonecrosis. The document states that radiological screening is needed for divers who dive deeper than 30 msw or spend more than 20 hours per week underwater. Two paragraphs later the publication recommends that all new graduates should be considered for initial screening. Periodic screening is then recommended for those who routinely dive deeper than 30 msw with a total dive time of over four hours. This would include deep air and mixed gas diving in addition to saturation diving. Screening in the past was performed by x-ray evaluation of the long bones, but Magnetic Resonance Imaging (MRI) is expected to be the standard method used in the future.

Discussion

Generally, diving organizations did not require additional medical standards based on diving depth. (Two exceptions will be discussed later.) It is the author's impression that the additional medical fitness required of a diver who dives deeper than 190 fsw is much less than the initial medical fitness required to dive to 190 fsw.

In addition, organizations typically rely on the examining physician to determine if a particular diver is medically fit to perform a particular type of job in a particular working environment. In Europe, much emphasis is placed on the qualifications of the examining physician, while in the US, practically no such emphasis is made.

Physical fitness was not discussed because there were no specific additional requirements for deep diving in any of the organizations reviewed. In addition, physical fitness at the time of diving medical examination may be greatly different from that at the time of the dive. It is up to the Dive Supervisor (or equivalent) to determine if the diver is sufficiently physically fit to perform the dive based on the work required and the work environment.

One exception that gives an additional depth-based medical requirement is the Canadian Forces proposed PFO workup and repair policy. In the author's opinion, the concept of using a scale other than a simple presence-or-absence of PFO to restrict diving is a step in the right direction. On the other hand, the use of an interventional cardiac procedure to implant hardware in an otherwise normally-operating heart, where that hardware will remain for the rest of the diver's life, is concerning. However, the author is woefully ignorant of such hardware, and instead is influenced by his experiences at the Navy Experimental Diving Unit where occasionally a manufacturer's claim of a device's reliability differed significantly from reality.

Since the Canadian Forces policy would apply to all dives deeper than 49 fsw, AAUS adherence to the policy would affect general AAUS diving, and not just deep diving. Thus the paper is able to defer this contentious issue to the general AAUS diving medical standards policymakers, assuming that diving deeper than 190 fsw will create venous bubble loads no greater than those encountered in AAUS diving less than 190 fsw.

The other additional medical requirements exception deals with dysbaric osteonecrosis, a recognized problem, but one that hasn't had the glamour or investigative funding for quite a few years. Both the Royal Navy and EDTC require initial and periodic radiological surveys for dysbaric osteonecrosis. The current HSE guidance states that routine x-rays are not required before undertaking saturation diving unless osteonecrosis is suspected. However, this policy may simply reflect great concerns about the risk of radiation exposure.

When queried by the author about dysbaric necrosis, David Elliott responded with an informative letter[20] that provided an overview of screening divers for dysbaric osteonecrosis. In the letter, he states:

> "Bone necrosis is a particularly complex clinical subject and is in an already difficult area of employee health but *there seems no doubt that the scientific divers will be at increased risk when compared with those diving within the safer envelope of conventional and shallower procedures.* Those divers do need some form of specific health surveillance."

He then provides his reasoning why the preferred method of monitoring divers is through periodic x-ray surveillance, although he recognizes that it is becoming an unacceptable procedure due to the hazards of radiation exposure. At present, MRI is felt unsuitable for diver screening because it is too sensitive in the early asymptomatic phase of dysbaric osteonecrosis, and the lack of appropriate epidemiological studies. An additional factor is the much higher cost of MRI compared with x-ray procedures. In a follow-up document[21], he offers a possible pathway for evaluating dysbaric osteonecrosis and other avascular necroses.

Conclusions/Recommendations

In general, AAUS scientific diving standards appear adequate for diving to 300 fsw.

If AAUS is satisfied with the performance of the physicians who currently examine AAUS divers, then continue to use them.

For AAUS divers who will work deep, or spend multiple hours at a time underwater, consider developing a screening program for dysbaric osteonecrosis using David Elliott's recommendations as a starting point.

There is no need to consider an additional PFO policy for deep diving unless it is known that the deep diving decompression schedules will give divers significantly higher venous bubble loads.

Issues related to dysbaric osteonecrosis and PFO are not unique to the deeper diving discussed in this meeting and could therefore affect currently accepted diving practices at SI and in the scientific diving community in general. A consensus on the proper methods to screen divers for dysbaric osteonecrosis and PFO may take significant time. In the author's opinion, it is unnecessary to delay diving to 300 fsw while awaiting a consensus, since the probability of an adverse event is low with either condition, based on current diving practices at AAUS and in the US in general.

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US NAVY DIVING PROGRAM: DIVING TO 300 FT DEPTHS USING SURFACE-SUPPLIED AND SATURATION FLY-AWAY DIVING SYSTEMS

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Introduction

Diving to 300-foot ocean depths began early in the last century exclusively through use of surface-supplied diving equipment. With the advent of self-contained apparatus in the 1940s, technological advances safely permitted short duration diving to depths approaching and even exceeding 300 feet. Nonetheless, for bottom times greater than 15 minutes, surface-supplied diving continues to retain a number of advantages over current self-contained rebreather technology. For really long bottom times, measured in hours instead of minutes, saturation diving is the most efficient and efficacious method to accomplish work at ocean bottom depths.

This paper addresses the U.S. Navy's mixed-gas surface-supplied and saturation diving equipment and capabilities. For many reasons beyond the scope of this paper, U. S. Navy diving systems greatly exceed what is required in many commercial diving operations, and almost all scientific diving operations. Frequently, U.S. Navy diving systems are designed to substantially different requirements than standard commercial diving equipment and, therefore, are much more costly, sometimes by an order of magnitude than commercial counterparts.

Surface-Supplied Diving

Although equipment and procedures exist in the U.S. Navy diving program to reach depths as deep as 300 feet of sea water (fsw) using closed-circuit rebreathers (in particular the USN Mark 16 Mod 1 using a 1.3 ata constant partial pressure of oxygen), almost all deep working dives employ mixed-gas surface-supplied diving systems instead. The rationale behind preferred use of surface-supplied systems is straight forward:

1. increased safety associated with direct umbilical connection to the diver;
2. improved communications between topside and the diver;
3. greatly improved thermal protection through use of umbilical-supplied hot-water suits; and,

4. ability to employ surface-decompression on oxygen (sur-D-O_2) techniques, which greatly reduce the diver's in-water decompression obligations.

Figures 1 and 2 document the substantial in-water decompression differences between 300 fsw dives for similar bottom times of the U.S. Navy Mark 16 Mod 1 decompression tables and the U.S. Navy Helium-Oxygen sur-D-O_2 decompression tables. Additional advantages to the use of surface-supplied systems for deep ocean working dives include safer means to achieve significant internal wreck penetration, use of video cameras, and communications tethered to the diver. These allow many more "topside experts" to engage with and direct the diver on task, and a greatly improved "turn-around" of dive team rotation by use of sur-D-O_2 (next dive team can deploy as soon as first dive team is safely locked down in the recompression chamber undergoing decompression on oxygen).

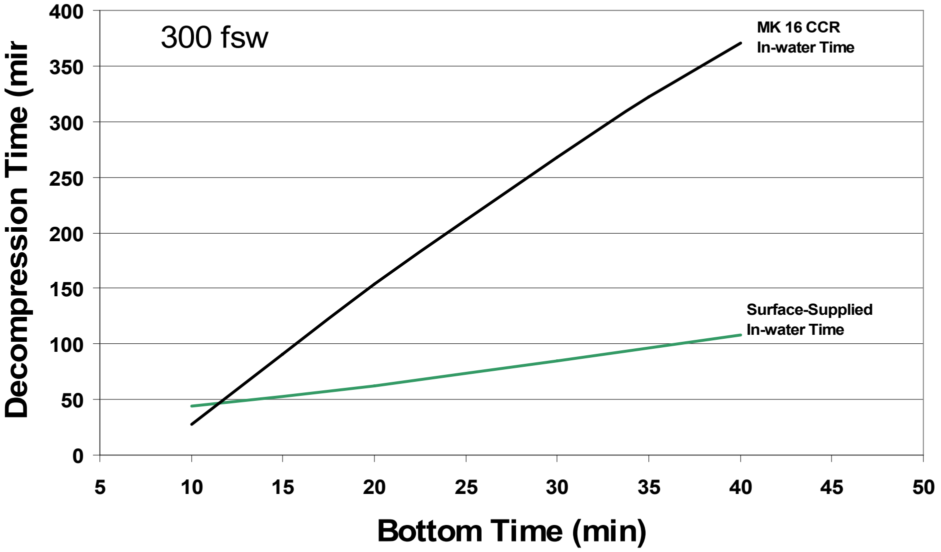


Figure 1. In-Water Decompression Obligations (Surface Supplied vs. MK 16 Rebreather).

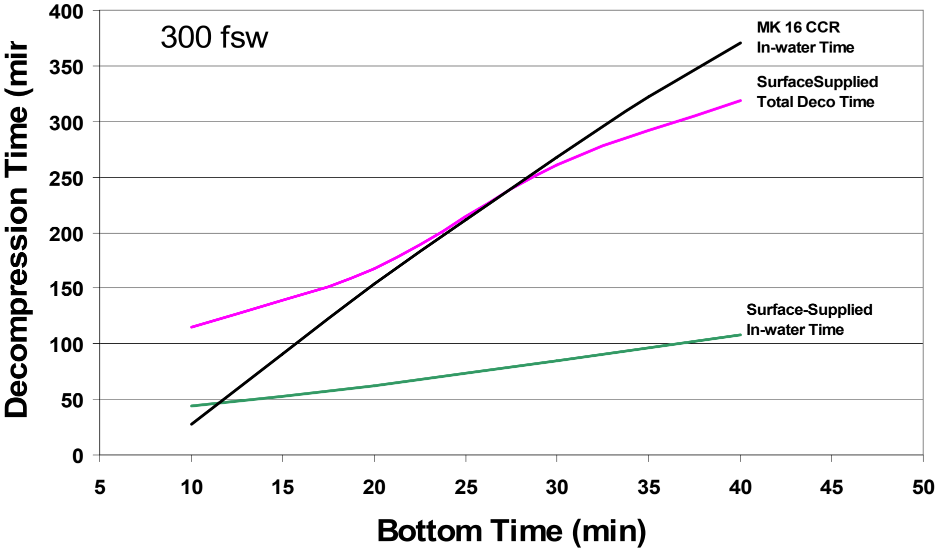


Figure 2. Total Decompression Obligations (Surface Supplied vs. MK 16 Rebreather).

Surface-supplied diving does have disadvantages over closed-circuit deep diving. Many working scientists may prefer the improved diver mobility resulting from elimination of the topside umbilical connection. Further, several closed-circuit rebreathers, though by no means inexpensive, generally can be purchased and supported for much less than a full mixed-gas surface-supplied system, certainly much cheaper than the U.S. Navy "Fly-Away Mixed Gas Diving Life Support System" a.k.a. FADS III. The manning of a surface-supplied diving team generally is 2 to 3 times larger than that required for a closed-circuit rebreather team.

Fly-Away Mixed Gas Diving Life Support System

In recent years, the U.S. Navy Diving Program developed a modular system of diving components that can be assembled to provide either air (capable of diving to 190 fsw) or mixed-gas surface-supplied diving (capable of diving to 300 fsw). Since this workshop is intended to address diving to depths of 300 fsw, the mixed-gas capability is described below. The FADS III was designed to support gas capacities for 2 divers simultaneously diving to depths of 300 feet with maximum bottom times of 30 minutes, and decompressing on helium-oxygen surface decompression on oxygen (HeO_2 sur-D-O_2) tables. Additionally, sufficient gas is provided to support a third "stand-by" diver to 300 feet for 30 minutes in the unusual circumstance that one or both of the primary divers gets fouled on the bottom and needs assistance clearing himself. This is not a small system; it requires approximately 325 square feet of deck area, and weighs in at 38,000 lbs. The good news is that it can be easily transported in component parts, and is "ruggedized" to withstand any mode of transportation, from standard over-the-highway trucking, to rather high-impact vertical landing on decks when transported as suspended external loads under helicopters.

Figure 3 provides a cartoon schematic of the principal FADS III components. The primary breathing gas system is the Helium-Oxygen Supply Rack Assembly (inevitably called the HOSRA) composed of nine composite high-pressure (5000 psi) storage flasks (each of three cu ft floodable volume) contained in a rigid open cube structure for transport and storage. Typically, two HOSRA are used to configure the FADS III. The HOSRAs are recharged as necessary with a 5000 psi heliox boost pump assembly. Oxygen for decompression and treatment gas is supplied through an OSRA or Oxygen Supply Rack Assembly, fundamentally similar to the HOSRA, but charged to 3000 psi. Accompanying the OSRA is an oxygen boost-pump assembly for OSRA recharging. Of course, we need an ASRA (Air Supply Rack Assembly) for recompression chamber operations, and in an extreme emergency, in-water air decompression tables. The ASRA is backed up by a 5000 psi air compressor assembly. All of these gases are regulated to the divers through the mixed-gas control console assembly (which strangely has no particular acronym, it's just called the "console"). Any number of recompression chamber configurations can be used with the FADS III, but generally, the U.S. Navy deploys one of our containerized "Standard Navy Double-Lock" or SNDL chambers to round-out the FADS III system.

Typically, at least 13 dive team members are required for each shift of deep surface-supplied mixed-gas diving. If several weeks of continuous 24 hours per day operations are desired,

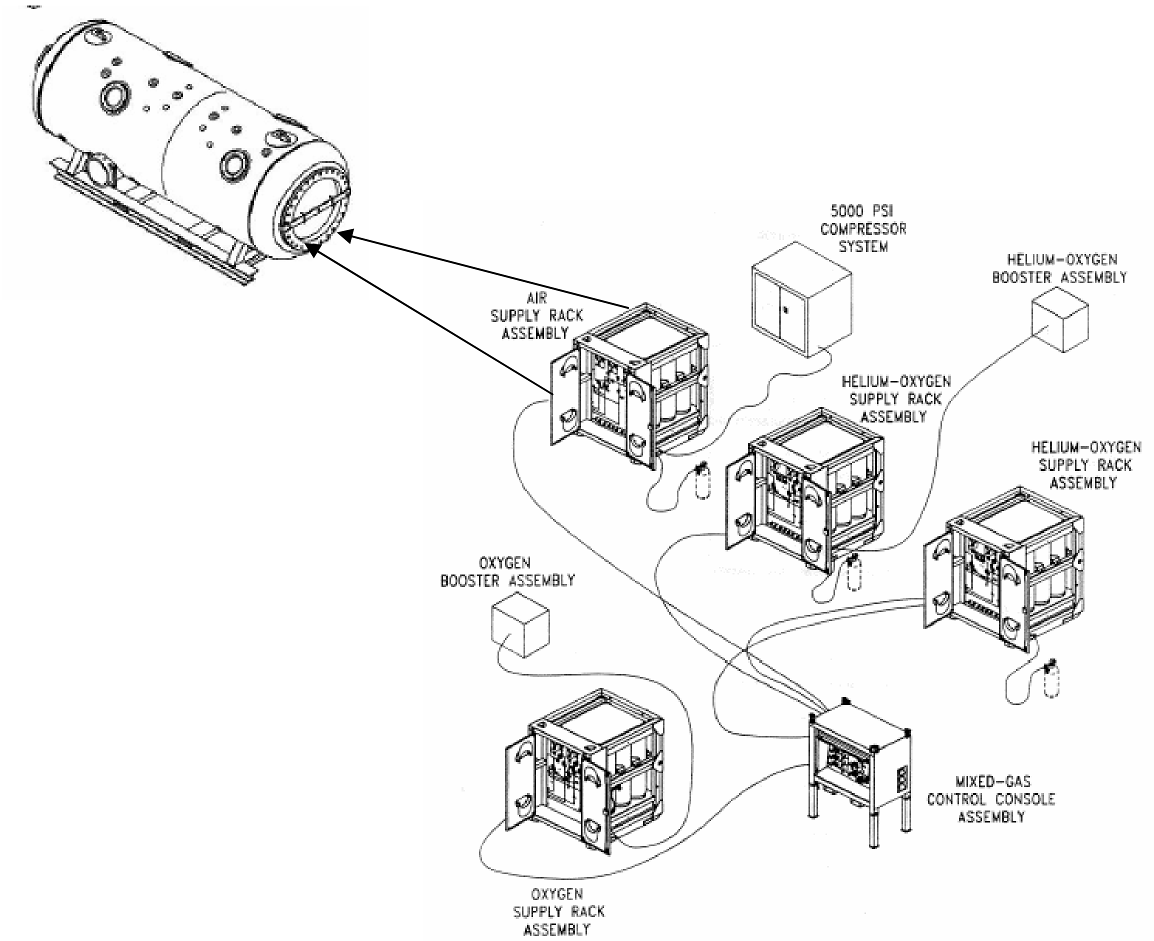


Figure 3. U.S. Navy Helium-Oxygen Fly Away Mixed-Gas Diving Life-Support System (aka FADS III) With Recompression Chamber.

our experience indicates approximately 24 personnel are required per 12-hour shift (or 48 personnel per day). On each shift, the minimum U. S. Navy personnel requirements include:

- 1 Diving Officer
- 1 Master Diver / Diving Supervisor
- 1 Medical Diving Technician or Diving Medical Officer
- 3 Divers (1 is a Stand-by Diver)
- 5 Diver-tenders

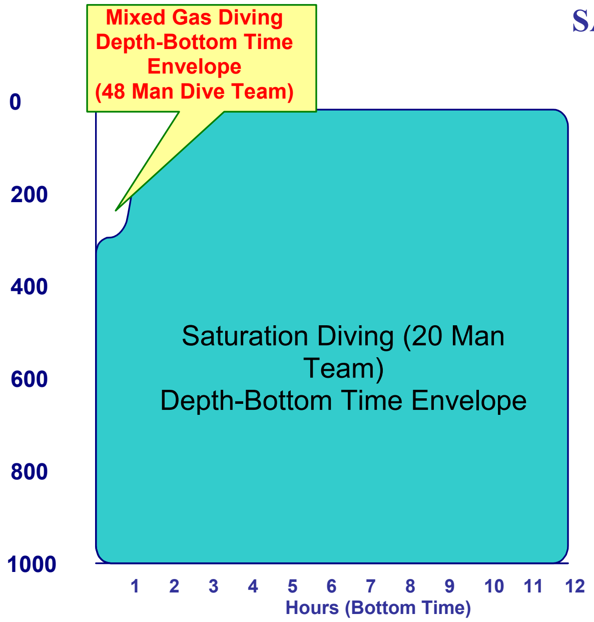
- 1 Gas-Rack Operator
- 1 Winch Operator (to operate the divers' stage)

Saturation Diving

If long-duration operations to depths approaching or exceeding 300 feet are required, a much preferred approach, and in the long-run often a much less expensive (including manpower), is to use saturation diving. The benefits of saturation diving are by and large obvious, with the principal benefit being essentially unlimited bottom time. A direct advantage of saturation diving over surface-supplied diving for long-duration operations is that of individual diver learning-curve. For many surface-supplied operations, the actual effective bottom time is substantially less than the total bottom time. Travel times, deployment from the stage to the work-site, and recovery of the diver from the work-site to the stage prior to leaving the bottom all directly detract from productive work on the site. Even worse, changing out divers so frequently almost invariably leads to working the proverbial two-steps forwards and one-step back every time a new shift of divers deploys. Saturation divers, on the other hand, have a much smaller personnel rotation, so their familiarity and job-specific expertise builds instead of retreats on each job, in many cases accelerating work production with each subsequent dive rotation.

Saturation Versus Surface-Supplied Diving

Each of these benefits was quantifiably measured during U.S.S. MONITOR recovery efforts in 240 fsw off Cape Hatteras (the Graveyard of the Atlantic) during the summers of 2001 and 2002. U.S. Navy divers worked side-by-side with both types of systems, deploying from a 2-man saturation bell while at the same time conducting surface-supplied mixed-gas operations. Undeniably, the success of the operations during both summers was strictly due to the extraordinary work capacity of the saturation diving team. Had the saturation system not been used, MONITOR's engine and turret would still lie in ruins on the ocean floor continuing to corrode instead of now curated in their preservation tanks ashore. A graphical comparison of the operational window of saturation diving, as well as a side-by-side quantification of saturation diving work efficacy and efficiency as compared to surface-supplied heliox diving are presented in Figure 4.



SAT Diving Operational Envelope

Enhanced Capability

Manpower (sailors/24 hour ops):
Surface Supplied - 48
Saturation – 20
➢58% manning reduction

Productivity (bottom time/24 hour ops):
Surface Supplied < 9 Manhours/Day
SAT >24 Manhours/Day
➢267% improvement

Saturation – 3x depth, 4x efficiency, & 40% manning

Figure 4. Operational Envelope and Comparative Advantage of Saturation Diving versus Surface-Supplied Diving.

Conclusion

As the U.S. Navy embarks on procurement of a highly-portable Saturation Fly Away Dive System (SAT FADS), we are interested in finding joint operational missions with NOAA and the science community to allow us to operationally deploy, train, and maintain proficiency of our saturation diving community, but also to productively engage in further development of scientific research. When deployed in 2007, the SAT FADS will access 100 % of the world's continental shelf, permitting scientific exploration of a largely unknown frontier. SAT FADS operations will prove efficient from both a cost and work accomplished standpoint in depths as shallow as 150 feet of water (air saturation) to 700 feet and greater (heliox saturation). Anyone with potential scientific missions willing to cost share operations of this nature are invited to contact the Office of the U.S. Navy Supervisor of Salvage and Diving (202.781.0731), or email us through our website at www.supsalv.org.

COMMERCIAL DIVING: SURFACE-MIXED GAS, SUR-D-O_2, BELL BOUNCE, SATURATION

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Introduction

In the commercial diving world, mixed-gas diving usually begins around 180 fsw and is limited by the U.S. Coast Guard to 300 fsw, except in California OSHA waters, where surface diving to 350 fsw is permitted. It is virtually always sur-D-O_2. To this author's knowledge, no commercial in-water decompression tables exist for mixed gas. Excessively long in-water decompression times would present risks and operational difficulties for the diver.

Decompression Tables and Incidence Rates

In general, three HeO_2 tables are in current commercial usage: the Oceaneering International (OI) Alpha tables, the old American Oilfield Diving (AOD) Company gas tables (also referred to as 50/50 tables), and various modifications of the USN Partial Pressure Tables. Bubble growth analyses of the Alpha's show them to be a relatively safe table, yielding approximately one undeserved bend in nearly 800 dives (as reported by former Corporate Safety Director Terry Overland, on Oceaneering's multi-year experience). There are no data for the Alpha-like AOD tables, yet some report them to be even better than the OI Alpha Tables. This author has used a slightly modified form of these AOD tables for three years in a small commercial company, having no cases of DCI in just over 300 dives. Personal experience with the Ocean Systems modification to the old Navy partial pressure tables resulted in a higher rate of DCS. These tables were again modified by SubSea International using the bubble growth models (Gernhardt/Lambertson/Miller) to eventually yield a safety record equivalent to the Alpha's while having an average of 10 – 15 minutes more bottom time. However, it is enlightening to compare these rates with the one undeserved bend in approximately 1500 decompression dives routinely experienced using commercially modified Navy sur-D-O_2 air tables and one in over 4000 decompression dives using the Lambertsen/Gernhardt/Miller/Beyerstein Next Generation sur-D-O_2 air tables. Using the USN tables as published, both pre-1995 and later, yields an unacceptably high rate of DCS and no commercial company would consider using them unmodified today.

Sur-D-O_2

Surface decompression using oxygen is a technique where the diver performs some in-water decompression stops, comes to the surface exposed to one atmosphere for a limited period, and then is recompressed in a double-lock deck decompression chamber. A decompression mix of 50/50 nitrox is usually employed, specified by the AOD and Alpha tables, for a portion of the in-water decompression, normally beginning at 90 fsw but never deeper than 100 fsw. The use of pure oxygen at 50 fsw and 40 fsw in the water as per older Navy doctrine is now universally no longer practiced in the commercial world. In the deck chamber, common recompression practice is to descend to 50 fsw for 10 minutes breathing oxygen, ascend to 40 fsw where the majority of the decompression takes place, followed by a 10 minute ascent to the surface. Oxygen breathing in the chamber is interrupted by air breaks, usually on a :20 and :05 or :25 and :05 minute schedule.

Bell Bounce Diving

Bell bounce diving was once quite prevalent commercially, being well suited to drill rig intervention diving. This market is now the exclusive province of the ROV world, and commercial bell-bounce diving has disappeared. For normal operations it offers no advantage and requires equipment, crew, and training similar to a full saturation diving system. It may possibly find a use in the scientific world, as it applies to a requirement for limited-bottom time deep dives, matching the scientific mission profile. Depending on depth and duration, the diver enters a saturation decompression mode during his decompression.

Bell bounce diving tables were problematic resulting in many bends. Oceaneering had the Yankee tables and SubSea had the SSM7 tables from Virginia Mason University. Other companies used tables from several sources, Allan Krasburg being one. The tables were all high ppO_2 decompression tables. SSM7's used 0.7 ppO2, modified Bühlmann used 0.8 ppO_2. The divers all hated them as they came out "crispy" from high pulmonary oxygen toxicity.

The drill rig diving arena of the North Sea diving experience, during the mid to late '70's, was responsible for most of the many diving fatalities experienced in those days (See *Requiem for a Diver*, by Jackie Warner, former UK Diving Inspectorate Head). Rig divers came out of dive schools and were immediately employed as commercial divers, not tenders. The limited diving involved with drill rigs meant many days of idleness followed by a deep dive in a hurry. The time pressure was intense. Most of the incidents had root causes in diver inexperience and lack of training, something to consider for the scientific community contemplating this diving mode.

Saturation diving

Saturation diving requires the heaviest resource commitment. First of all, the diving platform, vessel, or barge, has to be large enough in deck space and quarters. It can be anchored if the diving is not too deep, but the usual commercial mode now is dynamic positioning (DP), where computers are fed sensor data to enable control of various combinations of thrusters to hold the vessel in position over a spot on the bottom. To be diving certified, a DP vessel must be multiply redundant, having no possibility of a single point failure. Diving can be over-the-side or through a moon pool, a hole in the center of the ship. In its ultimate expression, a specialized purpose-built diving support vessel (DSV) with heave-compensated crane, ancillary support ROV, two moon pools with identical dive-control rooms, and two three-man bells with heave-compensated lift wire/clump weights and cursor launch system, is employed. A system such as this can keep 2 divers working on the bottom continuously for 24-hours days, diving in practically any seas. Operations such as this usually involve a second boat to deliver diving gas, groceries, water, and fuel as well as helicopter transportation for crew changes. A sixteen-man system can be split, allowing diving to two simultaneous depths. Such a system is very expensive and probably considerably beyond scientific diving needs or expectations for the foreseeable future.

300 fsw Scientific Diving Options

In this author's opinion, aside from ROV's, there are two viable options for the scientific diver wishing to personally sample at depths to 300 fsw.

Atmospheric diving suits (ADS) is the first system to consider, of which two viable commercial units exist. The Wasp, used by Oceaneering among others, and the Newt Suit or Hard Suit, courtesy of Phil Nuytten from Canada, used by Stolt and other companies as well as the USN as part of their submarine rescue program. Both are excellent units. The main advantage is long-duration dives with virtually no decompression requirement in a shirt-sleeve environment. Other advantages include the need for a smaller launch platform, smaller footprint, and reduced crew size. Any science operation would probably require at least one trained operator and one technician. Two units are always employed, one serving as a rescue diver. They are tethered, increasing the safety margin, and the technology has progressed to the point where thrusters give extensive mobility. Sample collection would not involve heavy hand work, negating one of these units' greatest limitations, limited strength and dexterity of the hand "claw". The units are relatively high maintenance but have an excellent safety record. Training would be involved, provided by the vendor if units were purchased. Extensive experience can be easily gained in a tank or pier side without the expense of a vessel. This option should be seriously explored by the scientific community.

The second 300 fsw scientific diving option is surface-supplied mixed gas diving. In it's elemental form, this diving mode involves a control manifold (gas rack), helium unscrambler radios, two dive helmets with diving hoses, oxygen analyzer, two 5120 air diving compressors, a double-lock deck decompression chamber, an open bottom bell and launch system (davit or A-frame), dive ladder, supplies of oxygen, 50/50 nitrox, high-pressure air, and pre-mix HeO_2 Divers can dive to moderate depths in temperate water in wet suits. For deeper diving or diving in colder waters, hot water suits and a hot water machine are necessary. This package could easily fit on a 130-foot supply boat if there was a location to tie up to. Otherwise, a four-point anchor boat is required for diver security. Diving on a single hook is considered unacceptable. Crew size could be as small as a Diving Supervisor, two divers, two tenders and a rack operator. Depending on training and experience, if the scientists were willing to work on deck, then perhaps four scientific divers backed up by a commercial Dive Supervisor and commercial rack operator could safely fill the bill for a minimal operation. As experience and confidence is gained, the need for professionals would decrease.

Considerations

Depending on the table employed, a minimum of 18 to 24 hours must elapse between dives. Multi-day, multi-dive missions tend to build up a high CPTD load for the divers, resulting in pulmonary decrement. Although this is temporary and recovery completes in a few days, it can increase the risk of DCS and result in decreased diver efficiency on the bottom. For practical applications, operational consideration must be given towards maximizing productivity by balancing vessel costs with time required on bottom, involving increased equipment, and larger crew size. A second chamber is usually employed so another diver can dive while the first is finishing decompression, or therapy if required, so that operations will not stop. If sufficient deck personnel are employed, one diver can be decompressing in the water while another begins a dive. The times must be carefully controlled so that a chamber is always available for all divers, including emergency considerations. This may mean a third chamber. Every additional chamber requires a 5120 air compressor and oxygen bank, with resulting increased deck equipment footprint. The dive mission and budget will determine the equipment/vessel/crew mix.

It might be useful to consider a maximum exposure to 300 fsw on the Alpha table to maximum allowed duration (operational planning limit) of 30 minutes. Bottom time is from leaving surface to leaving bottom. Allowing 4 minutes for descent to bottom, and a 2-minute “leave bottom early” safety cushion (always done in the commercial world) this result in 24 minutes of useful bottom time for the scientist. The decompression schedule requires a total of 95.6 minutes in the water at various depths breathing gas to 170 fsw, air to 90 fsw, and 50/50 nitrox to the surface. On surface, the diver then has one and a half minutes to get up the ladder or off the stage (open bottom bell), across the deck, and into the chamber. He must be recompressed to 50 ft in 30 seconds and go on oxygen within 3 minutes. He will then spend a total of 223 minutes in the chamber breathing oxygen in 20 minute periods with 5 minute air breaks. This is a total dive time of 379 minutes (6 hours, 19 minutes) from leaving water surface to reaching surface after completing deck chamber decompression for 24 productive minutes on the bottom. The scientist can write a report or read a book in the chamber, but little else.

This was the worst-case scenario. Shallower dives require less decompression, but chamber time is a price commercial divers pay for doing their work, and highlights the need for saturation diving for tasks requiring extended bottom times. These lengthy decompression times could be reduced by a technique called “repeting-up” used commercially for air diving. Unfortunately, no commercial multi-depth gas diving tables exist or are in use by any company. However, the technology exists to develop such tables. There is little need for them in the commercial arena, or they would have been produced long ago. The IFEM models, Gernhardt/Lambertsen/Miller, such as were used for the highly successful Next Generation Air Tables this author participated in at SubSea, could successfully be used to develop multi-depth HeO_2 tables, but testing of new tables is problematical and there are many obstacles to overcome, not the least of which is funding.

Training

The issue of training must be addressed. Scientific divers are undoubtedly very experienced scuba divers. Diving with surface-supplied equipment is not a great leap forward as far as the in-water component. Dive helmet familiarization and training is necessary as well as experience with hose control. Diving with a hot water suit is effortless. If the suit is well compressed (used), no weight belt is necessary, nor is a buoyancy compensator. Commercial divers normally do not use a dive computer or depth gauge either. Some use a compass, needed to determine which way to direct the crane, etc. The diver wears a bail-out bottle. The scientific diver will appreciate the freedom from equipment encumbrances that surface-supplied diving entails, once he gets used to the helmet and dragging a hose around. Topside controls the dive, depth, table, task, and time. The dive is aborted if communications are lost. The scientist may miss the independence he enjoys as a scuba diver. The dive supervisor’s word is law, to be obeyed without question. He will have to learn standard hose commands and dive terminology. Bear in mind that in the commercial world, the new employee first attends a dive school, dedicating 6 months and perhaps \$12,000-\$17,000 towards commercial diver education. He will be hired as a tender. After gaining experience and proving himself, he progresses to diver tender, then after perhaps 1 ½ to 3 years or more, “breaks out” to Grade III diver. As the years and his skill progresses, he is promoted to Grade II and eventually, to Grade I. Normally, a diver must be at least a Grade II to gas dive, and this takes, in a normal market, at least 3 - 5 years. To be eligible for a saturation position will certainly take longer, as this attainment is recognized as the pinnacle of his profession.

It may be helpful to examine the Association of Diving Contractors International (ADCI) minimum requirements for a mixed gas diver, consisting of formal education, field experience (*i.e.*, technical proficiency) and number of working dives. Formal training at an accredited dive school must equal a minimum of 625 hours in specified subjects. A minimum of 317 hours of formal training can be supplemented by a minimum of 308 documented hours of on-the-job training in specific subjects if the entry-level diver does not have the specified hours of formal training. These are the minimum standards for entry-level Tender Diver. To achieve air diving certification, the individual must have a minimum of 100 field days of air diving operations plus 30 working dives of at least 20 minutes bottom time, all performed within 24 months prior to issuance of the designation and under proper supervision documented by a log book certified by his company. To progress to mixed gas diver, the individual needs an additional 50 days of mixed-gas diving activity plus 10 working gas dives. In practice, the commercial diver usually exceeds these requirements by a healthy margin before being trusted to dive on a gas job. These are minimum requirements.

The commercial gas diver is a thoroughly competent individual, familiar with all aspects of the diving operation, including tending, equipment set up, operation and routine maintenance, chamber operation, fixing the hot water machine and even "running the rack", *i.e.*, controlling the gas console during a dive. It is in these topside considerations the scientific diver will be found lacking and needs training to be a functioning member of a dive crew, not just a diver showing up on deck for a dive. In the beginning of the program, these elements will have to be supplied by a commercial diving company, and undoubtedly on-the-job training will be a major element towards gaining eventual operational independence from commercial supervision. A formal qualifications program, perhaps a training passport with skill sets signed off while on the job, should be set up to further this process. The ADCI's Consensus standards for Commercial Diving Operations will be a useful guide and reference in this regard.

Other Important Considerations

A situation currently exists that is unprecedented in the commercial diving field. Nearly all deep diving occurs in the Gulf of Mexico and is oil patch related. The oil fields, infrastructure, platforms, and pipelines in this area have been devastated by three successive powerful hurricanes. In 2004, there was Ivan and the oil patch was still repairing damage from that storm when in 2005 Katrina and then Rita ripped their way across the Gulf. Damage was extensive and vastly under-reported by the media. Over 100 platforms were sunk and more than 1,000 damaged. Pipelines were torn up and production decimated.

This situation has resulted in a greatly increased need for divers and their equipment. Floating assets have been drawn from all over the world. Vessels are working at the time of this writing that under normal conditions would previously never have found employment, being much too large and expensive. The pool of offshore divers decreased over the past few years and is now fully employed. Rapid expansion has diluted the general level of competence. Inland divers and companies have relocated there as well as new start-ups blossoming at never before seen rates. Prices have risen sharply and everything is scarce: equipment, divers, and particularly experienced Diving Supervisors and Superintendents. This author, after leaving the field and spending 26 years in commercial diving management, now finds himself back offshore project managing a multimillion dollar job on a 454 ft dynamically positioned Canadian vessel relocated from Mexico with a crew of 96 persons. The entire saturation dive crew is Mexican, which is unprecedented. Vessels, rental diving equipment, systems, divers, welders, riggers, crane operators, cooks, vessel masters, none are to be found.

This is a situation expected to last for several years due to the extensive damage. These factors will prove difficult to overcome when the scientific community goes shopping for equipment, vessels, or a diving contractor. Assuming a diving contractor of required quality can be found, the price will be extravagant. The contractor will have liability concerns that need to be addressed. Care must be taken to ensure that no inexperienced inland companies are employed. These companies are now hired for work they are not really equipped to perform. Having spent last fall as an Oil Company representative Inspector working with just such an inland company, personal experience saw employees called divers that by Gulf standards were barely competent tenders. The 130 ft supply vessel we were diving from normally costs $3500 per day at a premium day rate. When it blew an engine and we had to hire a similar vessel of the same size, the price was $4500 per day, and that only a month after the storms. Now one would be hard pressed to pay less than $5500. Similar increases are found across the board. This situation, while temporary, will exist for an extended period of time and must be considered by the scientific deep diving program manager.

Conclusion

In conclusion, this author believes that two viable options should be explored to develop a useful 300 fsw scientific diving capability. One is the Atmospheric Diving System (ADS), which is initially equipment expensive. It is doubtful a contractor could be found that would initially allow use of his equipment rented by scientists, even under his crew's hired supervision. By the purchase of two of these units, with assistance from the vendor and perhaps a contractor, training could progress rapidly and independent capability generated in a reasonable time. Once a track record is produced, it may be easier to find commercial contractors willing to let scientists dive their equipment as operations expand.

The second viable option is surface-supplied mixed gas diving, at first possibly by scientific divers backed up with a commercial contractor's crew and equipment. Training for the scientific diver to use surface-supplied diving gear would be relatively limited and soon achievable from several possible sources. Full program independent capability will take longer in order for the scientist to function as a full topside crew member using his own organization's dive system. Such equipment is easier purchased with long lead times at present than rented as a system from the contractor. Qualified commercial contractors willing to place a scientist on the bottom using his crew and equipment may be difficult to find in this current premium market, and liability concerns would have to be addressed.

It may be easier to develop the desired capability by hiring a qualified independent consultant(s) from the commercial world and purchasing a full diving equipment system. Current prices from Diver's Supply in New Orleans for a full system would run less than $200,000. A detailed price breakdown is provided as an attachment to this paper. Vessel platforms may exist “in house” and could be more easily contracted than the other option of using a commercial contractor. A crew of commercial divers and a supervisor could be independently hired to supervise and run the deck operations while training the scientific divers. Training programs and operational procedures manuals could be developed with such independently contracted assistance. This way the entire operation is “in house”, under full control, freed from outside restrictions such as regulatory bodies and trade organizations, and can proceed as funding and personnel become available.

Attachment A. System Equipment Prices.

Vendor quote 02.22.06:
Diver’s Supply
2396 Bell Chasse Hwy, P. O. Box 1663
Gretna, LA 70054
504-392-2800 Ph, 504-392-3920 Fax

Product: Gas-Diving Package for 2 Divers

Qty	Item Description	Cost ($)
2	5120 Quincy Compressor with 1250 filtration	49,500
2	Decompression Chamber, 54”, double-lock, plumbed	59,990
2	Mattress, Fire resistant foam	378
6	Bib Masks	5,730
2	Chamber Radio	770
2	Oxygen Regulator	438
3	600’ 4 member umbilical, color coded, tested and certified	5,607
6	Deck Whips, 50’, ½” hose with #10 JIC fittings	720
4	HP (5000psi) deck whips	1,040
1	Gas Rack 1B (2lp, 4hp, 3 pneumo gauges)	7,495
2	Radio, Helium unscrambler	5,200
2	Kirby Morgan Helmets	10,000
2	Hot Water units	20,000
3	Hot Water Suits	4,200

1	Open Bottom Bell (Class II)	9000
2	Oxygen Analyzers	800
1	A-Frame launch system	25,000

*Stand-by air supply not included. (could be provided by a HP air bank)

Approx. Total $196,000

Options:	Cost ($)
Torch and 600’ lead w/ hose	3,305
Ground Lead 600’	1,778
Knife switch	202
Single Diver Radio	479
Breathing Air Regulator (CGA-346)	219
80ft^3 Scuba Bottle	140

commercial diving: 90 mSW operational aspects

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After the collapse of the offshore diving industry in the 90's, there still remains a need for conducting bounce diving operations down to at least 90 m. The development of technical diving has brought new options in terms of the diving methods. Although heliox is still the best bottom mix, trimix appears as a good compromise for the depth range considered. However, decompression safety is the key to such operations. Former bounce diving tables from the offshore and military diving have too high DCS incidence rates. New tables need to be developed. The design of a table requires deciding upon a critical bubble scenario. Using the arterial bubble assumption, it is shown that at least to aspects of the bubble growth need to be controlled: the bubble radius in the earlier stage and the bubble volume in the later stage of the decompression. The review of the classic models shows that they only cover one aspect of the decompression. The new bubble growth models do produce deep stops but miss the last part of the decompression. A new model is presented that combines the two aspects in a multi-model approach to decompression safety.

Introduction

The North Sea operations had leadership in commercial diving from 1970 to 1990 and set standards, regulations, code of practice for the whole industry. Since the success of ROVs and deep subsea operations, commercial diving has much recessed and its technology has stagnated.

Diving operations are still running in the air diving range. They include inland diving, military diving, search and rescue, scientific diving, fishery, and recreational diving. Because of the collapse of the offshore industry, these divers need to fill in the gap and extend their operational capacity to at least 90m. The most active group are the technical divers, who have already integrated and adapted some of the professional techniques to extend their explorations. In light of the past commercial diving experience and the rising technical diving achievements, several options are reviewed that could support new bounce diving operations to 90m.

Diving Procedures Options

Commercial diving methods of intervention are well defined in the local laws, industry regulations and company's manuals. However, each job having its own tools, methods may differ from one diving site to the other. The classic commercial diving methods of intervention include (1):

- SCUBA diving, to a limited extent. This method has a limited gas supply, no communication with the surface, and in most cases, no safety link between surface and the diver. SCUBA diving is forbidden in the North Sea.
- Surface-supplied is the preferred method of intervention. The diver is supplied from the surface through an umbilical that provides him with gas, communications, a safety line, a hot water hose for his heating, a TV cable, etc. The diver can be deployed from a basket. The bottom mix can be air or mixed gas, the decompression mix nitrox or pure oxygen at 6 m. Decompression procedures include in-water decompression or surface decompression in a deck chamber.
- Wet bell diving. The divers are deployed into a wet bell with a gas filled dome. The wet bell provides more comfort and controls and allows for longer time in water. Wet bells are used for air and mixed gas, and because of the dry environment in which they are sitting, divers can take oxygen on a mask at 12 m.
- Bell bounce dive. Small bell systems have been designed that can be easily mobilized and include a two-man bell, a handling frame and a chamber for TUP. Divers can breathe air or mixed gas at the bottom but are usually recovered in the chamber filled with air. They perform pure oxygen breathing sessions on mask by the end of the decompression. Small bell systems support bounce diving down to 120 m and for bottom times up to 2 hours.

Commercial diving has rugged and proven methods but the requirements for the surface support are heavy. Unfortunately, after ROVs took over manned intervention, a lot of small bell TUP systems were put aside and later scrapped. It would be difficult to mobilize such systems nowadays. New methods of intervention have been developed recently by the cave and wreck divers that are lighter and cheaper:

- The trimix "tech" configuration where the diver carries his bottom mix in a twin cylinder set on his back and clips one or two stage cylinders on his harness as decompression gases. The evolution in the equipment (double-wing BCD, steel back plate harness, argon dry suit, DPV, etc.), procedures (tables, trimix computer, dive planning) and training (risk analysis, what if sessions, etc.) has turned SCUBA diving into a safer and more efficient method permitting reasonable intervention up to 90 m (2). The best technical divers now explore to depths in excess of 150 m and the deepest dive performed was 330 m.
- Rebreather diving, once the monopole of military divers, is now a common practice in technical diving. The offer is large (Inspiration, Evolution, Megalodon, KISS, etc.) and the training is available through specialized agencies (IANTD, TDI, etc.).

At least several options are now available for extending bounce diving operations. One particular issue is related to the PO_2 control during the decompression. Deep bounce decompressions represent a heavy off-gassing process and divers need to adopt an aggressive oxygen protocol during their ascent. In open circuit, the diver has to change his decompression mix to raise the PO_2 during the ascent. The PO_2 profile looks like saw teeth. The CCR divers have the possibility to breathe constant PO_2 during the entire ascent. Despite the longer training and heavier maintenance, CCRs represent a new way to more efficient decompression. However, it is admitted that their use in commercial diving still requires solving several safety problems (degraded conditions, bail out situation, link with surface, etc.).

Bottom Mix Options

The choice is between heliox and trimix. Apparently a simple issue that requires some considerations.

Heliox is certainly the best bottom mix, as proven by the North Sea construction. It is also the best decompression mix. This is more difficult to document as air tables and heliox tables seldom overlap. It is also biased by the fact that heliox tables are deeper, less used, and certainly less accomplished. At least, in saturation diving, heliox decompressions appear much faster than air decompression (3). Dr. Fructus, who designed most of the Comex tables in the 70's, used to say, as a man of experience, that helium is much "easier" than nitrogen.

The main limitation of heliox is its cost. This is why heliair (a simple blend of air and helium also called "poor man mix") and trimix were invented. Trimix was also chosen to avoid the need to use a speech unscrambler and to cut down on the respiratory heat loss associated with heliox, an important point for divers using passive thermal protection.

In France, trimix was developed in the 70's based on the French Navy tables (4) and their further adaptations. See Appendix 1.

In the USA, to my knowledge, trimix was introduced by André Galerne at the IUC Company. In the early 80's, the US Navy collaborated with the Royal Navy on some trimix tables testing at the Deep Trials Unit. Later, with the advent of deep cave diving, Dr. Bill Hamilton used his DECAP model to cut tables for cavers Bill Gavin and Parker Turner during their dives at Indian Spring. The WKKP used trimix intensively for the exploration of the Wakulla Spring system. Caver Sheck Exley designed his own trimix tables. Finally, when technical diving started in the early 90's, new trimix tables became available through decompression software and dive computers.

Despite its operational success, trimix is based on a trade off of gas density and narcosis. Trimix divers evaluate narcosis with the concept of the equivalent air depth (EAD) and usually dive with an EAD between 30-40 m. They select mixtures depending on depth and the specified values of the bottom PO_2 and EAD. Table 1 lists trimix mixtures used in technical diving. Heliox breathed in closed circuit loop could be a way around that. Limiting the cost and providing the full benefit of helium, the CCRs again present an attractive alternative.

Table 1. Trimix gas mixtures used in technical diving.

Trimix gas	Operational depth range
T20/25	40-60 m
T19/30	50-70 m
T16/40	70-80m
T14/50	80-90 m

Decompression Table Options

Safe decompression procedures are the key to the development of bounce diving to 90m.

Previous experience with commercial diving tables is worrisome. Table 2 below presents the safety performances of a set of heliox tables called "Cx70" that were used by the Comex Services Company between 1970 and 1982. The tables were available in two versions. The first one was designed for surface-supplied diving and limited to 75 m. The diver breathed heliox as bottom mix and 100% oxygen at the 6 m stop. The second one was designed for bell TUP diving and provided exposures up to 120 minutes, down to 120 m. The diver breathed heliox in water and in the bell, air once transferred in the deck decompression chamber, and finally oxygen on mask from 12 m to the surface. The overall incident rate was around 4% and thus far exceeded the tolerated decompression sickness (DCS) incidence of modern tables that range between 0.1%-0.5% (5). Most of the symptoms were type I pain only DCS. However, a significant number of type II DCS symptoms, essentially vestibular hits, were recorded in association with the short bottom times.

Table 2. Safety performances of the Comex Services Company Cx70 heliox decompression tables used between 1970 and 1982.

Table Cx70	Exposures number	Type I number	Type I rate	Type II number	Type II rate	All DCS number	All DCS rate
Surface supplied	1450	18	1.24 %	3	0.2 %	21	1.4 %
Bell TUP	3820	140	3.6 %	15	0.3 %	145	3.8 %

One might minimize the risk by recalling that this corresponded to the state of the art. People were trained to identify the symptoms and apply recompression procedures as soon as the diver reported a problem. This way, in most cases, the symptoms were relieved and the DCS treated. However, the concern is that a lot of symptoms occurred at depth, a situation that has no consequence when inside a bell or a chamber, but that turns critical when the diver is hanging at his decompression stop in the water. No treatment is available and no access to the surface is possible. Moreover, if the symptoms involve the vestibular function, the diver is likely to vomit, a dramatic situation when breathing from a regulator. For this reason, tables using in-water decompression must have an additional safety margin to insure that no symptoms will occur while the diver is in the water.

Recent experience with technical diving tables is more reasonable. IANTD, a technical diver training agency developed by Tom Mount in the USA, uses trimix tables for diver education that are typical of a prudent approach. The tables are based on a classic Bühlmann model but have additional built in precautions that make them longer and more conservative. They are far from being optimal but that is not the objective. Although no official safety records are published, my experience with IANTD training in France culminates in:

- 534 divers exposures performed between 42 and 60 m (IANTD trimix 20/25 tables),
- 105 exposures between 63 and 69 m (IANTD trimix 19/30 tables),
- 315 exposures between 72 and 81m (IANTD trimix 16/40 tables),

and not a single decompression problem was reported for 954 dive exposures.

But the tables lack flexibility and the trend is towards computer diving. Divers have now a large choice of commercially available decompression software and dive computers. There are currently 5 families of models used for trimix diving:

- The classic Bühlmann algorithm (6) as in the Voyager dive computer,
- Bühlmann algorithms adapted with extra deep stops as in the VR3 dive computer and Pro Planner software, from the Delta P company, UK,
- Bühlmann algorithms modified by the gradient factors method (7) as in the GAP software.
- VPM algorithm of Dr. David Yount (8) as in the V Planner software,
- RGBM algorithm of Dr. Bruce Wienke (9) as in the Abyss software.

It is difficult to evaluate the safety performances of these decompression tools because there is no independent organisation that could collect the information and turn it into scientific data. There is also a lot of concern in the way the computers are used. A recent paper published on trimix DCS cases treated at the hyperbaric chamber of Toulon suggests that inadequate training, equipment and procedure can lead to serious decompression accidents (10).

Decompression Table Calculation Options

The traditional "Haldanean" models work on dissolved gas. These models cannot be denied certain efficiency since the present commercial air diving tables have an overall safety record around 0.5% DCS incidence (11). The question is their relevance for deeper diving. Such models have a strategy of an initial rapid ascent to create an off-gassing gradient. Their profile is typical. Such a strategy is now questioned and current empirical practices rather tend to slow down the initial part and introduce additional deeper stops. It is obvious that extending the operational range will require different models to produce different profiles. We need to bolt a new model layer onto the existing one.

Analysis of bounce tables indicates that the dive profile controls the bubble formation and decides on the safety outcome of the decompression. As the profile is related to the exposure, it seems that, with the existing tables:

- Short bottom time tables (10-30 min) characterized by a rapid ascent to shallow stops produce vestibular symptoms,
- Average bottom time tables (30-90 min) produce other neurological symptoms
- Longer bottom time tables and saturation diving, associated with slow ascents, produce type I pain only DCS in the last meters of the decompression.

Such facts support the following new vision of decompression modelling:

- The DCS risk must be appreciated separately for each symptom,
- Each symptom depends on a different bubble scenario,
- Each bubble scenario must be associated to a different model.

The arterial bubble assumption allows for the structuring of this concept (figure 1). Arterial bubbles were already mentioned by Haldane on page 352 of his 1908 publication (12). Closer to our time, in 1971, Hills (13) was able to show, using an animal model, that DCS symptoms could change from Type I to Type II by changing from continuous decompression to surface decompression, thus suggesting different mechanisms. Later in 1989, Hennessy published the physical aspects of the arterial bubble scenario in a paper (14) that became the foundation of the arterial bubble assumption.

The issue in the arterial bubble assumption is the filtering capacity of the lungs. The threshold radius is suspected to be the size of a blood cell. During the initial phase of the decompression, when bubbles are small, they are likely to pass trough the lungs into the arterial side. Later in the ascent, bubbles grow to a larger size and remain trapped in the lung.

The arterial bubble assumption introduces variability in the decompression outcome through the lung function. It is reasonable to accept that the filtering capacity of the lungs may vary from person to person, and for one individual, from one day to the other. It thus accounts for the inter-individual variability (age, fat content, smoking, etc.) and intra-individual variability (fatigue, hang over, etc.), which has been observed for a long time in DCS susceptibility. Basically, a good diver is a good bubble filter. The arterial bubble assumption is also consistent with the accidental production of arterial bubbles.

One scenario is related to the diver’s physiology. It considers shunts at the heart or lung level that accidentally pass bubbles from the venous to the arterial side. A vast literature is now available on the subject of permeable patent foramen ovale (PFO) (15). The studies have shown a high correlation between central neurological DCS and the detection of a permeable PFO (16). A permeable PFO conveniently explains neurological accidents after recreational air diving without any procedure violation.

Another scenario is related to the diving procedures. It considers pressure variations during decompression that reduce bubble diameters. This way; bubbles trapped in the lung during a normal decompression could suddenly cross through the capillaries and later generate type II DCS symptoms. This explanation has been proposed for the difference in safety performances between in-water decompression and surface decompression (17). Data collected in the North Sea have shown that if the overall incidence rate of the two diving methods is about the same. However, surface decompression tends to produce ten times more type II DCS than in-water decompression. The scenario is that at the moment the diver ascends to the surface, bubbles are produced that are stopped at the lung level. Upon recompression of the diver in the deck chamber, these bubbles reduce their diameter due to Boyle's law and go to the arterial side, later causing neurological symptoms. The same scenario was proposed for type II DCS recorded after yoyo diving or multiple repetitive diving.

Finally, the arterial bubble assumption provides an explanation for the criticality of the initial ascent phase. Bubbles associated with symptoms are not necessarily generated on site. There is an amplification process at the beginning of the ascent that may last for several cycles. Once the bubbles have reached a critical size, they are either filtered in the lung or stopped at the tissue level. It is believed that the showering process of small arterial bubbles during the first minutes of the initial ascent prepares the prognostic for further DCS symptoms. It is consistent with the current empirical practice of deep stops and slower rates of ascent.

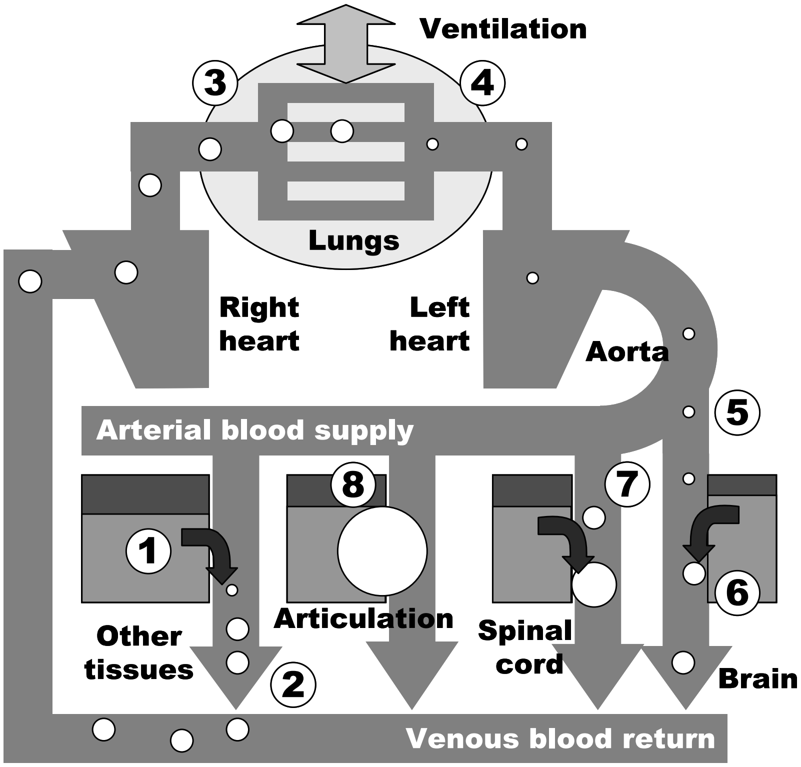

Figure 1. The Arterial Bubble Assumption

1. Diving requires breathing a compressed inert gas that dissolves in the various tissues during the bottom exposure. When the ascent is initiated, the compartments off-load the inert gas as soon as a gradient is created.
2. Bubbles are normally produced in the vascular bed and transported by the venous system to the lung.
3. The lungs work as a filter and stops the bubbles in the capillaries by an effect of diameter. Gas transfer into the alveoli further eliminates the bubbles.
4. The critical issue is the filtering capacity of the lung system. Small bubbles may cross the lung and pass into the arterial system.
5. At the level of aorta cross, the distribution of blood is such that the bubble is likely to reach the brain via the carotids.
6. The brain is a fast tissue and might be in a supersaturated state in the early phase of the decompression. It acts as a gas reservoir and feeds the bubble that starts growing. The bubble may just proceed to the venous side for another cycle. It may also grow in place causing alteration of the blood supply and finally ischemia. The

The rationalization of the arterial bubble assumption requires two models covering two situations (figure 2):

- In the initial phase of decompression, the critical event is the arrival of an arterial bubble in a de-saturating tissue. The site is a neurological tissue. The bubble exchanges gas with the surrounding tissue and the blood. The strategy for a safe rate of ascent is to balance gas exchanges. If the bubble does not exceed a critical radius, it will eventually leave the site without growing. In the other case, it will block the blood circulation and cause ischemia. The bubble radius is the critical parameter. The condition is used to prevent type II neurological symptoms.
- In the last phase of the decompression, the critical event is the presence of a large bubble that has drained a large quantity of dissolved gas from the near-by tissue. The site is an articulation. The strategy for a safe ascent is to prevent any gas phase to grow beyond a critical volume. If the bubble reaches a critical volume, it will have a mechanical effect on the nerve endings causing pain in a tendon. The bubble volume is the critical parameter. The condition is used to prevent type I pain-only symptoms.

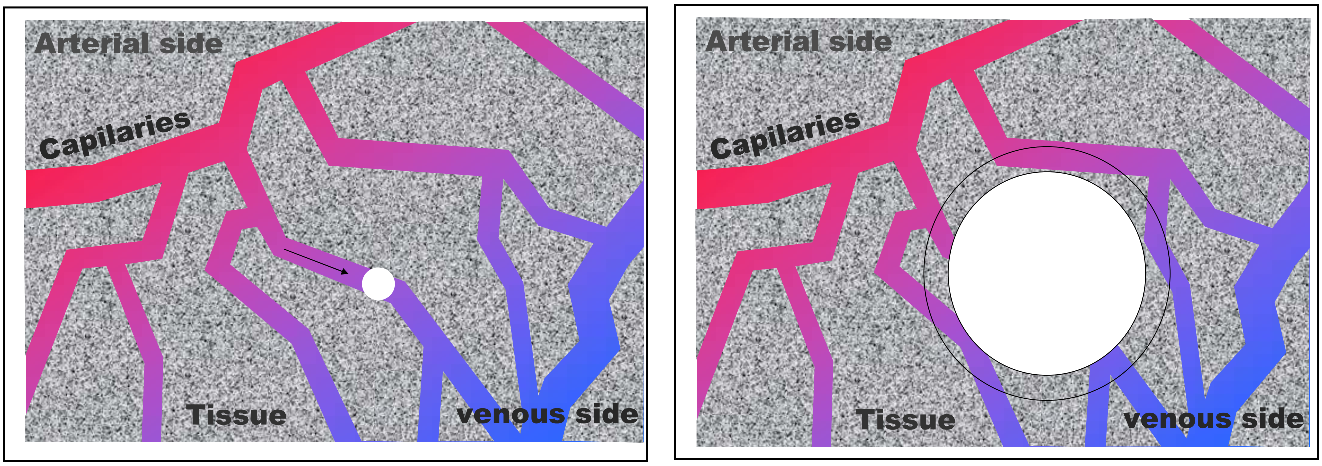

Figure 2. On the left, in the initial phase of the decompression, an arterial bubble enters a tissue capillary net. It exchanges gas with the surrounding tissues and starts growing. If it reaches a critical radius, it might block the blood supply and cause ischemia. On the right, in the last phase of the decompression, a bubble has grown to a large volume using dissolved gas available in the surrounding tissue. Its mechanical action might cause pain.

The critical volume concept was developed by Hennessy and Hempleman (18) who formulated a simple mathematical condition linking the dissolve gas and the safe ascent pressure:

$$Ptis_{gas} \leq aPamb + b$$

Where P_{tis} represents the dissolved gas tension, P_{amb}, the ambient pressure and a,b two coefficients. This linear relationship between dissolved gas and ambient pressure has the same mathematical form as an M value. It suggests that all the Haldanean models (including the US Navy tables, the Bühlmann tables and all the French tables), are just an expression of the critical volume condition, regardless of the justifications presented by their authors. This has some serious implications on the currently available algorithms.

First, if we admit that dissolved gas models only control large volume bubbles, they only deal with one part of the problem that is the prevention of type I DCS. Effectively, such models work perfectly with saturation diving where type I DCS is the concern (3). They could also work at shallow depths because the initial ascent phase is short. We know that they must be adapted (slower rate, deeper stop, etc) when used with deep bounce diving, where neurological symptoms are the concern. The reason is that they missed the initial part, the bubble growth process and the critical radius assumption.

Second, if we admit that bubble growth models may adequately control the initial part of the decompression, they might miss the final part of the decompression. For instance, the popular VMP algorithm, with its complex thermodynamic study of a bubble population growth, produces decompression profiles with very deep stops. However, close to the surface, stops become shorter than the equivalent Bühlmann model. It is suspected that this algorithm over-emphasizes the initial problem, the bubble radius, but underestimates the second one, the bubble volume.

The truth must lie between the Bühlmann and the VPM algorithms. There must be alternatives.

One possibility consists in modifying the Bühlmann algorithm using gradient factors. It modifies empirically the M value and twists the dive profile to produce the deep stops. The method works beautifully but the problem is the definition of the gradient factors. Of course, because the technique is purely empirical, it has no predictive value. A set of different values must be found for each depth and time component.

Another alternative consists in combining the two issues. We recently developed and published the arterial bubble model or “AB model” (19) that follows the two states of the bubble growth (Appendix 2). The algorithm produce tables with stops deeper than with a classic Bühlmann model but shallower than with the VPM model. The model was fitted with data from the offshore industry, both for air diving and heliox diving. It is being calibrated with trimix diving using deep cave diving and coral diving data. It represents a potential alternative to the exiting ones.

Conclusion

There is an operational pressure to extend bounce diving to 90 m. In this depth range, new methods of intervention are available such as the technical diving configuration or closed-circuit rebreather. For these methods, the most cost-effective mix seems to be trimix, a well validated bottom mixture. However, considerations on decompression safety and work performances may support the use of heliox, especially with rebreathers.

With such improved techniques, the key to safety remains the decompression procedure because past experience with the offshore industry has shown that the DCS incidence rate could be high. Recent development of technical diving has shown, however, that at least for short time exposures, the tables derived from the Bühlmann algorithm can provide a reasonable level of safety. However, for deeper or longer exposures, new developments are required.

The arterial bubble assumption provides a new vision of DCS mechanisms and proposes different bubble scenarios for the onset of the different symptoms. The concept is based on two critical events: one during the initial phase of the ascent when the size of the bubble is critical to avoid tissue ischemia, the second during the last phase of the ascent when the volume of the bubble is critical to avoid mechanical effects and pain.

The classic Haldanean model using a M-value mathematical formula seems to describe the second scenario, while the bubble growth model such as the VPM algorithm seems to only describe the first one. Decompression modelling now requires a multi-model approach that is illustrated by the recent development of the AB model. It provides the deep stops as in the new bubble-growth algorithms and the traditional end of decompression as in the dissolved gas algorithm.

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Appendix 1. History of Trimix Table Development in France

Trimix and heliair are part of our diving culture but the facts and the persons that led to their invention are lost in history. To my knowledge, part of the action took place in France.

In 1963, the French Navy unquestionably designed original trimix tables under the direction of Dr. Lucien Barthélemy. Cdt. Cousteau who commanded the GERS in the 50's (the French Navy diving department) had access to these tables and used them later during several expeditions and in particular during the Britannic dives in Greece to 105 m. The trimix tables left the Navy with Dr. Pierre Cabaroux when he joined the Sogetram, a large commercial diving company in 1970. They were used in conjunction with the semi-closed rebreather FGG III. André Galerne, one of the founders of the Sogetram, took them over to the USA when he left to set up International Underwater Contractors. André Galerne must have further developed these tables as IUC is known to have conducted heavy trimix operations down to 180 m.

The French tables crossed the border for a second time as Dr. Cabaroux went working at the DFVLR, in Germany. DFVLR ran a series of research programs on deep bounce diving in the 70's, that included trimix dives.

Later, the CG Doris Company took over Sogetram and got the trimix tables in that deal. The tables were revised with the help of the French Navy in a version now referred as the "Doris tables". They were later used intensively during a difficult dam repair job in Iran, when the war with Iraq made the helium supply uncertain.

Not far from France, Dr. Zanini in Genova, Italy, developed trimix tables, using surface decompression, for coral divers in Sardinia and in Ustica. The tables arrived in France through the Corsican coral divers who developed a generation of heliair tables that are still in use.

More recently, with the advent of deep cave diving, the Doris trimix tables were revived. In 1982, Jochem Hasemayer, a daring German caver, used trimix tables (apparently self designed) for his 220 m dive at Fontaine de Vaucluse in the south of France. Meanwhile in the USA, Dr. Bill Hamilton used his DCAP model to cut tables for Olivier Isler during his push at the Doux de Coly, in the centre of France.

Finally, with the advent of deco software and dive computers based on the Bühlmann model, trimix tables invaded the technical diving world. It must be remembered, however, that Dr. Bühlmann derived some excellent air tables, some less successful heliox tables, but never edited any trimix tables.

Appendix 2. Definition of the AB Model

Following the scenario of the arterial bubble assumption, the critical case is defined as the arrival of an arterial bubble in a tissue compartment (figure A2.1); it is assumed that:

- The bubble was formed elsewhere. Its growth did not modify the local tissue gas load.
- The bubble is reputed to be small when compared to the tissue gas capacity, at least at the beginning of the decompression process. It does not change the tissue perfusion time response.
- Stuck in place, the bubble exchanges gases with both blood and the adjacent tissue.
- However, the bubble is stable and keeps a critical volume.

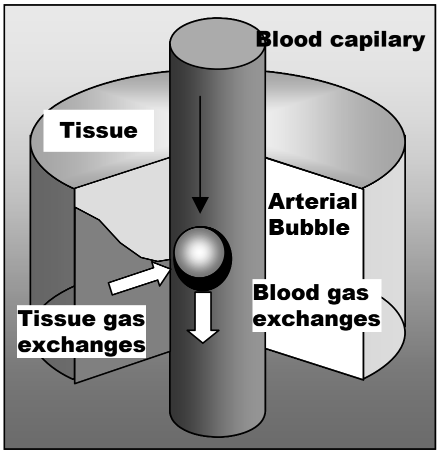

Figure A2.1. Definition of the critical case.

The Tissue Gas Exchange Model

Tissue compartments are just an historical approach and their identification is not important. The use of a series of compartments avoids the difficulty of accurately defining the process of the gas exchanges, whether perfusion, diffusion, or combined perfusion and diffusion. Thus, in this model, the exponential compartments are considered as harmonics of a complex mathematical solution that are control the decompression one after the other. For this reason, we used the general classic expression for compartment gas exchanges:

$$\frac{dPtis_{gas}}{dt} = \frac{0.693}{T}(Pa_{gas} - Ptis_{gas})$$

Where T is the compartment half-time as defined in the perfusion equation, P_a and P_{tis}, the arterial and tissue inert gas tensions.

The modern trend in table computation is to consider all the possible compartments and treat their half-times as a continuous variable. The difficulty then is to express the safe ascent criteria in terms of the compartment half-time. Because modern computers are fast, we decided to treat tissue compartments individually but express them with a geometrical series to remove any subjectivity in their selection. We used the Renard's series, named after a French admiral who faced the standardization of ropes, sails, planks, etc. in navy arsenals, and elegantly solved the problem with a geometric progression based on a square root of 10. For instance, with 10 values per decade ($\sqrt[10]{10}$), the series gives the following values:

10 - 12.5 – 16 – 20 – 25 – 32 – 40 – 50 – 63 – 80 – 100 minutes

Experimentally, we found that the computation becomes stable when the number of compartments is set in between 15 to 20 values per decade. This way, the description of the tissue gas exchange model only requires defining the boundaries. The fastest compartment obviously corresponds to instant equilibration and does not need to be specified. The slowest compartment is defined as the one used in saturation decompressions. Based on Comex saturation experience, these values were set at 270 minutes for heliox and 360 minutes for nitrox saturation. Finally, the tissue gas exchange model only requires one parameter to be defined, corresponding to the half-time of the slowest compartment.

The Bubble Gas Exchange Model

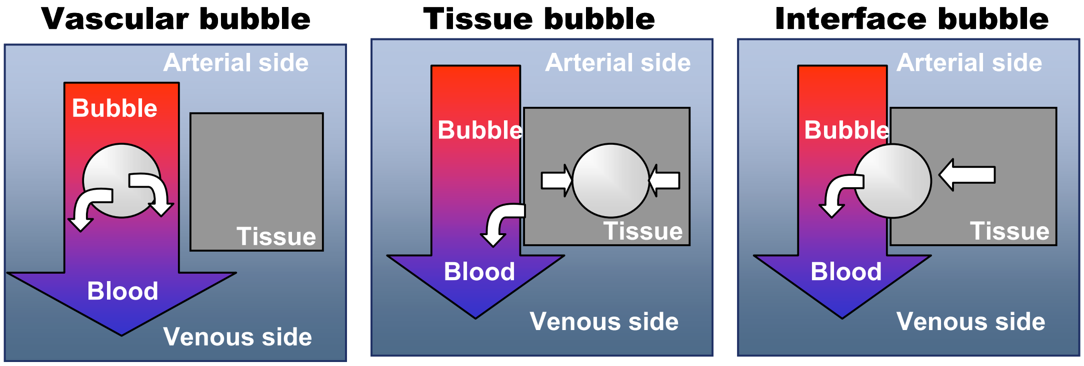

Figure A2.2. Possible bubble gas exchange situations.

To cope with the complexity of the inert gas exchanges in the bubble, we decided to simplify the process by considering two extreme situations (figure A2.2).

In one case, the bubble is purely vascular and remains in place. The blood flows around it and exchanges gas by convection so efficiently that there is no laminar layer and no diffusion delay at the bubble interface. In these conditions, we adopted for the bubble gas exchanges a formula similar to the classic tissue perfusion equation. We further assumed that the blood flow draining the bubble is a small fraction of the tissue perfusion and that the blood leaves the bubble equilibrated with its gas pressure. This permits an arbitrary expression of the quantity of inert gas molecules transiting through the bubble interface into the blood as:

$$\frac{dn,blood_{gas}}{dt} = C\frac{0.693}{T}(Pa_{gas} - Pb_{gas})$$

Where dn,blood$_{gas}$ is the number of molecules of inert gas passed from the bubble into the blood, Pa$_{gas}$ the arterial inert gas tension, Pb$_{gas}$ the bubble inert gas pressure, T the compartment half-time and C a coefficient that accounts for the fraction of the tissue blood perfusion that governs these exchanges, the relative capacity of the bubble to the surrounding tissue, etc.

In the second case, the bubble is purely extravascular. The bubble exchanges gas with the surrounding tissue by diffusion. We used the classic assumption of a linear gradient in a surrounding shell and obtained a second general expression for the number of inert gas molecules diffusing through the bubble interface from the tissue.

$$\frac{dn,tis_{gas}}{dt} = \frac{1}{K}(Ptis_{gas} - Pb_{gas})$$

Where dn,tis_{gas} is the number of molecules of inert gas diffusing from the tissue into the bubble, $Ptis_{gas}$ the tissue inert gas tension, Pb_{gas} the bubble inert gas pressure, K a coefficient that accounts for the diffusibility of the gas, the thickness of the layer, the surface of the bubble, etc.

Finally, we imagined an intermediate situation where the bubble is at the interface between the blood and the tissue and exchanges gas through the two above mechanisms. The importance of the exchange varies with the relative area of the bubble exposed to each medium. The ratio between the two exposed areas of the bubble is called α and varies from 0 to 1. The inert gas mass balance of the bubble becomes:

$$\frac{d(PbVb)}{dt} = R\tau(\alpha\frac{dn,tis_{gas}}{dt} + (1-\alpha)\frac{dn,blood_{gas}}{dt})$$

Where R is the gas constant, τ the absolute temperature and Vb the volume of the bubble.

The Safe Ascent Criteria

The ascent criteria simply seeks the stability of an arterial bubble, with a critical size, stuck at the interface of the blood vessel and exchanging gas with both the blood and the tissue. We translated this statement by specifying that the overall mass balance of the arterial bubble remains unchanged in these conditions:

$$\frac{d(PbVb)}{dt} = Pb\frac{dVb}{dt} + Vb\frac{dPb}{dt} = 0$$

This last condition means that the sum of all the internal gas pressures equals the external ambient pressure plus the stabilization pressures (surface tension, skin elasticity, tissue compliance). This is written as:

$$Pb_{gas} + Pb_{O2} + Pb_{H2O} + Pb_{CO2} \leq Pamb + Pbstab$$

Where Pb_{gas}, Pb_{O2}, Pb_{H2O}, Pb_{CO2} are respectively the pressures of the inert gas, oxygen, water vapor and CO_2 inside the bubble, Pamb the ambient pressure and Pbstab the sum of the various stabilization pressures.

Assuming Pb_{O2} is constant and equal to the tissue oxygen tension and introducing B, a coefficient of obvious definition, we obtained a simpler form of the criteria:

$$Pb_{gas} \leq Pamb + B$$

In these conditions, the total of gas transfers between the bubble and its surroundings are balanced. For each gas, the same amount of molecules enters and leaves the bubble during a unit of time. There is no gas accumulation inside the bubble.

$$(1-\alpha)\frac{dn,blood_{gas}}{dt} = -\alpha\frac{dn,tis_{gas}}{dt}\text{, and yields:}$$

$$\frac{\alpha}{K}(Ptis_{gas} - Pb_{gas}) = -(1-\alpha).C\frac{0.693}{T}(Pa_{gas} - Pb_{gas})$$

Finally, the two equations above are combined to eliminate Pb_{gas}. After defining another coefficient A, the final expression of the safe ascent criterion becomes:

$$\boxed{Ptis_{gas} \le (1+\frac{A}{T})(Pamb + B) - \frac{A}{T}Pa_{gas}}$$

This last equation sets the condition for a safe ascent to the next stop according to the initial hypothesis: an arterial bubble exchanging gas with blood and tissue that keeps a critical size during the ascent. It is a function similar to an M-value. With the tissue compartment tension perfusion equation, it permits the classic computation of a decompression stop time. The rate of ascent to the first stop is not part of the model control and is set arbitrarily to 9 m/min. The AB Model-2 provides deeper stops than for a classic decompression model.

A COMPARISON OF SURFACE-SUPPLIED DIVING SYSTEMS FOR SCIENTIFIC DIVERS

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Lightweight Surface-Supplied Diving Modes

Lightweight surface-supplied diving uses demand mode full-face masks (FFM) and/or free flow masks (Jack Brown). The typical lightweight (¼” internal diameter) umbilical supplies air to depths of 25 meters (80 FSW) or less. Below are five of the most widely used masks, as well as hookah, which employ a scuba half-mask with second stage regulator.

a. Jack Brown lightweight, free-flow full-face mask.
b. AGA
c. EXO-26
d. M-48 SuperMask
e. KMB band masks
f. Hookah

Advantages	***Disadvantages***
Safer than scuba	Limited to shallow depths < 25 msw (80 fsw)
Rapid deployment	Marginal Communications
Light weight, highly mobile	Minimal Redundancy
Multiple air supply sources	Poor Safety Record
Small package/footprint	
Minimal investment, maintenance and operational costs	
Minimal personnel required	

Lightweight surface-supplied diving incorporates a tether and communications, which makes this mode safer than scuba. It has a small footprint, can be easily transported by pick up truck or small boat, and is rapidly deployed. Multiple air supply sources can be used such as a small LP compressor or HP console fed from scuba cylinders. There is minimal investment, maintenance, and operational costs and it can be operated with a minimum of personnel.

Although limited to shallow depths (<25 msw - 80 fsw) with standard ¼” umbilicals, these full-face masks can be used well beyond this range when employed with umbilicals of 3/8” internal diameter, or specially designed intermediate systems for use with higher pressure ¼” umbilicals. These FFMs can, and do, employ communications. Most FFMs can be mated to a diver-worn manifold with a backup emergency gas supply (EGS).

However, many divers do not employ an EGS citing shallow depth diving. Some full-face demand masks allow for free-flow capability in addition to demand mode. Because of low start up costs, many divers with only scuba experience use lightweight equipment without proper training and therefore do not realize the potential hazards of surface-supplied diving.

Surface-Supplied Deep-Sea Helmet Demand Mode

Surface-supplied deep-sea demand helmet use is limited to a maximum depth of 200 fsw on air and 300 fsw on HeO_2.

Advantages	***Disadvantages***
Moderate weight	High supply pressure requirements for deep diving
Current compatible	Large gas storage or compressor system
Physical protection	Moderately heavy support system
In-water mobility	Deep mixed gas economically not feasible/ practical without reclaim
Contaminated water protection	
Gas-reclaim capability	
Various EGS options	
Doffing/donning ease	
Good communications	
Minimal open-circuit volume requirements	
Minimal gas usage in SCR	

Surface-Supplied Deep-Sea Helmet Free-Flow Mode

Surface-supplied deep-sea free-flow helmet use is limited to a maximum depth of 200 fsw on air and 300 fsw on HeO_2.

Advantages	***Disadvantages***
Heavy weight, good in currents	Large compressor/gas storage system
Physical protection	Large gas consumption
Contaminated water diving	Heavy, large footprint
	Large transport craft required
	Loud back ground noise
	Marginal communications
	Poor in-water mobility
	Limited EGS capability

Surface-Supported Alternative Modes

Surface-supported alternative methods use a specially configured, semi-closed or fully closed-circuit rebreather that is tethered from the surface or open bell. The rebreather systems use specially configured full-face masks or helmets equipped with an open-circuit demand regulator system for emergency use and shallow decompression. This method can use ¼” ultra-lightweight umbilicals weighing as much as 4 times less than conventional umbilicals. The system can be used as deep as 300 fsw from the surface and deeper if deployed from an open bell. This method enjoys the conservative gas use of rebreathers with the safety of umbilical support, including topside communications and monitoring. Monitoring can include loop PO_2, temperature, onboard pressures, and depth. The system also allows for topside intervention of components. This method has been used by the military as well as the commercial industry, but is not readily publicized.

Advantages	**Disadvantages**
Lightweight	Specialized training in equipment and procedures
Small gas use and storage requirements	Regular team training
Small footprint	Routine proficiency practice required
Real-time diver monitoring and override via the umbilical	Chamber support required
Open-circuit back up capability	

SCIENTIFIC DIVING OPERATIONS WITH UNTETHERED, OPEN-CIRCUIT MIXED GAS SCUBA

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In 1993, the NOAA Undersea Research Center at the University of North Carolina Wilmington (NURC/UNCW) began exploring the possibility of offering a technical diving program to visiting investigators for scientific research applications. The need for a technical diving capability was realized after a review of the attempts by the NOAA Diving Program (NDP) to support deep, mixed gas diving operations for a team of underwater archaeologists and scientific divers exploring the USS Monitor. The discovery of the wreck of USS Monitor established the first designated National Marine Sanctuary by NOAA and lies at a depth 240 fsw. Access to this site is considered by some beyond the reach of conventional, open-circuit compressed air scuba diving techniques. The review of this initial NOAA tethered, scuba diving effort lead NURC/UNCW to establishing a new diving program to support the scientific community wanting to conduct in-situ research beyond a depth of 130 fsw while safely exceeding the no-decompression limits using specialized techniques and equipment. NURC/UNCW currently possesses an in-house capability of supporting scientific research diving up to 300 fsw using untethered, open-circuit scuba technology. Each year NURC/UNCW supports at least one technical diving operation.

Introduction

The NOAA Undersea Research Center at the University of North Carolina Wilmington (NURC/UNCW) is one of the East Coast Centers funded by a grant from the National Oceanic and Atmospheric Administration's National Undersea Research Program (NURP) to support undersea research using divers, ROVs, submersibles and an undersea habitat. As a diving technology leader in the scientific diving community, the Center at UNCW constantly strives for ways to make scientific diving safer, more productive, and cost-effective. After an initial attempt by the NOAA Diving Program to conduct *in-situ* research at the USS *Monitor* deep-water archaeological site, NURC/UNCW began a planned progression towards developing an in-house capability to support technical diving operations, with the notion that advanced diving technology could be applied to other forms of marine science investigations.

Prior to 1993, the NOAA Diving Program had limited diving involvement on the USS *Monitor.* In that same year, NDP attempted to use a Class II, open-bottom bell and position a research vessel overhead in a 4-point moor for staging facilities and a recompression chamber to conduct the planned dives to the *Monitor*. The concept was that the bell would support two tethered, open circuit scuba divers and allow decompression to be conducted in the water, safely inside the bell. With the ship being held in a fixed, moored position, heavy seas and strong currents prevented dive operations during most of this 17-day expedition. Only three dives were completed. It was reported that divers were hampered by difficulties associated with controlling the bell and umbilicals in unpredictable seas and currents. The conclusion was that the operation was expensive, logistically complex, at times potentially hazardous, and ultimately unproductive. (Dinsmore and Broadwater, 1999). After review of this operation, NURC/UNCW submitted a plan to NDP to obtain a decompression diving capability for visiting investigators. NURC was impressed by its findings of the technical diving community efforts in refining open-circuit, mixed-gas scuba diving techniques, which eventually led both NURC/UNCW and NOAA program divers to request special technical trimix dive training from an outside vendor (Newell, 1995).

Technical Diving

Technical Diving is defined as “the use of advanced and specialized equipment and techniques to enable the diver to gain access to depth, dive time and specific underwater environments more safely than might otherwise be possible” (Palmer, 1994).

Specifically, technical diving occurs beyond a working depth of 130 fsw and incorporates mixed gases, although compressed air is still used operationally up to 150 fsw. The equipment used in technical diving is most always self-contained. Either an open-circuit scuba apparatus or rebreather is worn by the diver. Scuba is preferred by the research community because it is most commonly used for entry-level diving, it is relatively inexpensive, light weight and highly mobile, requires minimal support and maintenance, and is readily available off the shelf (Phoel, 2003).

To view technical diving from the proper perspective, it was developed to avoid having to use air for deep dives (Hamilton and Silverstein, 2000). Helium is added to the breathing mixture to reduce both oxygen percent and nitrogen percent, to help operate within safe oxygen exposure limits, and reduce nitrogen narcosis. This trimix combination, though costly, has numerous advantages for conducting technical diving operations. Dr. Morgan Wells developed a special mix of 18/50 (18% Oxygen/50% Helium – balance nitrogen), which became known as NOAA Trimix I or the “*Monitor* Mix”. This mix was conceived more for operational flexibility, than for physiological reasons. Filling the cylinder half full of helium and then topping off with Enriched Air Nitrox (NOAA EANx 36), easily prepared the balanced dive gas. Decompression Tables developed for NOAA by Hamilton Research, Ltd. and were used for subsequent years on NOAA and NURC combined *Monitor* projects (Hamilton, 1993).

Gaining Experience

Investigation of the training requirements and components for technical diving was obtained directly from a technical diving leader, Captain Billy Deans of Key West Divers, Inc. Deans was contracted by the *Monitor* National Marine Sanctuary to provide initial dive training for the NOAA Divers and to help support the next NOAA field expedition to the *Monitor* conducted in 1995 (Kesling and Shepard, 1997).

After this first NOAA/NURC expedition in 1995, NURC contracted Benthic Technologies, Inc., a technical dive training agency to get additional NURC staff divers trained and qualified for technical diving and to obtain instructor credentials for its leadership staff to conduct in-house technical diver training and certification programs for future visiting investigators requesting this new technology.

Equipment

After initial training efforts commenced, it became apparent for NURC to establish a new dive locker with enhanced diving equipment and capabilities. As the Center gained more experience with field operations, the dive locker was expanded with the necessary equipment to support technical diving. One of the benefits of technical diving is that the diving equipment used is similar to what scientific divers are already familiar with. Though packaged in a new configuration, the equipment consists of double scuba cylinders, redundant two stage scuba regulators and wing-style buoyancy compensators, a back plate with harness, mask, fins and either a wet or dry suit for diver thermal protection. Additionally, small cylinders of either steel or aluminum are configured with a two-stage regulator and carried by the divers. Much of this equipment is obtainable off the shelf. Most diving programs have the capability of maintaining the equipment in-house to keep it in good working order. Divers can also utilize this equipment for other routine dives, like those not requiring decompression or mixed gases to maintain proficiency.

There is an up front investment $3,500 to fully outfit one diver with a complete set of technical diving equipment. NURC helps defray the initial cost for this purchase by the visiting investigator by maintaining a dive equipment inventory for six divers to be used on an as-needed basis, or until such time that the research team can acquire their own personal dive equipment. The equipment is configured and standardized for this research diving team training by NURC. Technical dive equipment is relatively compact and is easily transported to the research sites or loaded aboard research vessels.

NURC also owns fixed and portable gas mixing equipment systems, which help to compliment the equipment needed for conducting field operations. This ancillary support equipment and gas mixing systems are much smaller and easier to transport to the dive site than those used for other diving technologies.

Training Programs

NURC has helped to establish a community standard for operating these new techniques by contributing to the American Academy of Underwater Sciences' *Standards for Scientific Diving,* which addresses both decompression diving and mixed gas scuba (AAUS, 2003).

Early in the development phase of technical diving for science, NURC/UNCW was asked by its National Undersea Research Program (NURP) sponsor, to establish operating standards and procedures for this new technology entitled, *Standards and Procedures for the use of Technical Diving in Scientific Research (*NURC, 2004). These minimal operational guidelines and training standards cover a 10-day training progression with 13 open-water training dives. This training progression is a relatively short investment of time for the candidate. The training document and outline was modeled after the Standards and Procedures established by IANTD, USA and uses their course materials (IANTD, 2003).

The NURC training program was designed different from that of the recreational training agencies, as a progressive course moving logically from start to finish, with skills building upon themselves and incorporating all aspects of the four IANTD required course modules, thus reducing the repetition of information. Prerequisites for participants considering this training include:

- Certified to dive scuba;
- Current scientific diving medical examination;
- Enriched Air Nitrox certification;
- Authorization to dive through reciprocity or as a temporary diver with current CPR, first aid and oxygen administration certifications;
- Log book with 200 logged dives with a min. of 30 deeper than 90 fsw; and,
- 25 logged dive between 140 fsw and 200 fsw or demonstration of sufficient experience for technical diving.

Training costs are based at roughly $1,500 per diver for the 10-day program. Additional costs incurred by the participants are travel, per diem, lodging, vessel charter, fuel, compressed gases for diving (helium, oxygen and EANx).

NURC has found that once the dive team is trained, technical diving operations become a fairly reliable system. The major key to success is ensuring that the divers maintain proficiency of their newly acquired diving skills. It is relatively easy to maintain proficiency by using the same diving equipment and configuration for other diving missions. Another key to success is maintaining good physical conditioning by the divers due to the rigors of the extreme environment and the bulk of the diver's dress.

Operational Support

Technical diving allows for greater flexibility when planning dive operations. Once dive team members are identified and training has been completed, then development of a detailed operations plan is formulated outlining both operational and contingency procedures for conducting the mission's field work. Technical diving can be adapted to many operational scenarios. The content of the operational plan includes an overview of the specific science objectives and lists the cruise participants, roles, and qualifications. The type of diving equipment to be utilized and necessary configuration is identified. Decompression strategies are also proposed. Ancillary support equipment is identified and safety procedures are outlined. Normal dive procedures and contingencies dive plans are covered in specific detail. This plan is peer-reviewed and, once approved, controls the conduct of the overall mission, thus keeping a rigid dive standard. Team selection and diver qualifications are important to overall mission success. There is also a large pool of trained users from the scientific diving community that can be called upon and cross-trained for a variety of science-related task and objectives. Additional training and pre-mission workup dives are conducted for all participants as needed. Drawing upon a pool of trained personnel can help satisfy more operational roles such as topside support, in-water safety diver(s) and standby diver(s) on deck.

When using self-contained, untethered scuba for diving there are more deployment platform options to select from. Small dive boats to oceanographic research vessels can be utilized. Since technical diving is usually conducted by free-drop diver deployments under "live boating" conditions, vessels are not restricted in their ability to maneuver. Divers can be deployed up-current, descend, and drift into the study sites, which makes the research sites more attainable, since maximizing bottom time is the greatest priority. The piloting skills of the research vessel captain are critical to this type of deployment and overall success of the mission. Because this type of deployment technique is preferred, diving operations can be conducted under a wide variety of surface and bottom conditions. Depending on team size, a large number of man-hours or divers can be supported. Mobility for the on-bottom divers has been the hallmark of technical diving operations for science.

Ancillary support equipment that may be required is smaller and highly portable (compressors, mixing equipment, DDCs). Breathing gases can be mixed on-site or delivered as "premix" in storage cylinders. Small hyperbaric chambers can be used in lieu of large, multi-place chamber systems. The *Hyperlite*, hyperbaric stretcher, is now a minimum requirement for all NOAA Diving Program decompression dives operating outside of a thirty-minute evacuation time to a facility. (NOAA, 2004).

The key to implementing a technical trimix dive is the ability to perform an efficient and reliable decompression that does not pose a substantial risk of oxygen toxicity

(Hamilton, 1999). Decompression planning and contingencies are handled by either consulting printed dive tables, dive planning software programs, or the use of diver-worn dive computers. Decompression procedures are planned ahead of time and primary and secondary decompression schedules are prepared and carried by the diver. The use of multi-gas, multi-mode decompression computers has provided far greater flexibility for conducting diving operations than printed schedules.

Field Operations

Before commencing a dive, the entire field operations team is briefed. Divers are dropped on the research site and begin the bottom phase of the dive. After the bottom phase of the dive, the team remains together and begins an ascent incorporating deep stops into the dive schedule either from published table or the use of a diver-worn decompression computer. In-water safety diver(s) are deployed and escort the team throughout the remaining decompression with gas switches to intermediate or primary hyperoxic breathing mixes, depending on depth. The in-water safety diver(s) are prepared to respond to contingencies of the dive team like low, or loss of, decompression gases. When reaching the 20 fsw stop divers switch to 100 % oxygen and are monitored for oxygen toxicity by the in-water safety diver(s). In some cases, oxygen is delivered via a surface-supplied regulator system. Once all required decompression is completed, divers surface and are recovered from the water. Back on deck, the diver team is thoroughly debriefed and alternate plans or improvements to the dive operations are discussed.

Statistics

Table 1 lists NURC/UNCW supported decompression/technical dives from August 24, 1994 to November 10, 2005.

Table 1. NURC/UNCW supported decompression/technical dives from 08.24.94 to 11.10.05.

Total Dives	2,376
Max. Depth	283 feet
Average Depth	173 feet
Max. Deco Duration	162 mins.
Average Deco Duration	51 mins.
Max. Bottom Time	40 mins.
Average Bottom Time	23 mins.

From this exposure dataset there have been three reported cases of decompression illness.

One case incurring lymphatic bends and the other two cases involving Type II decompression sickness with vestibular involvement. One DCS II case developed as a result of using published decompression schedules while the other occurred from a diver-worn decompression computer real-time profile. All three cases were eventually treated with recompression therapy.

Summary

Today, a technical diving capability is available to the marine science community from NURC/UNCW. The NURC Diving Program has established itself as a leader in technical diving for marine science research applications. NURC has the ability to support extended field diving operations and maintains an in-house infrastructure to handle gas mixing and cylinder filling, vessel operations, and personnel accommodations. It has a dive staff with expertise in technical diving that can serve as vessel captains, diving medical support, research divers, and dive station supervisors. Essentially, NURC offers a turn-key advanced diving operation to visiting investigators. The NURC model for safe conduct of technical diving can be applied to most marine science research projects where extended depth ranges and prolonged decompression is a consideration. The use of untethered, open-circuit mixed gas scuba diving operations has proven to be a productive tool for enabling scientists to reach depth ranges from 130 fsw up to 300 fsw.

Acknowledgements

The NURC/UNCW Diving Program wishes to thank the numerous organizations, divers, and scientific diving program partners that participated in NURC-led technical diving missions. Without their support and collaboration, technical diving would not have become a viable technique for use by the marine science community.

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APPLICATION OF DEEP DIVING TECHNOLOGY TO SCIENTIFIC EXPLORATION

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Introduction

In response to industry and military needs diving technology has developed dramatically in the last 20 years. Of primary interest to scientists today is the technology allowing divers to work at deeper depths, specifically depths between 50 and 100 m. Although there are scientists working at these depths, their numbers are relatively few. In order for deep diving scientists to become more commonplace the scientific community must develop new paradigms for applying this technology. Application of the deep diving technology is relatively straightforward requiring only minor adjustments to adapt it to scientific investigations. Development and institutionalization of standards, procedures, and administrative protocols specific to academic institutions may be the greater challenge. Development of funding mechanisms to support this activity and acquiring the necessary pool of experienced personnel also pose significant challenges.

Lead by the staff of the Center for Coastal Studies of Texas A&M University-Corpus Christi scientists and students from various universities of the Gulf States utilized deep diving technology including trimix, rebreathers, and deep air decompression dives in pursuit of scientific objectives. Most of this work was based from oil/gas production platforms off Texas and Louisiana in the northwestern Gulf of Mexico. This work was productive in expanding knowledge of the artificial and natural reef system dynamics and clearly demonstrated the value of deep diving technology to the pursuit of scientific objectives.

Technology

The research projects of the Center for Coastal Studies (CCS) teams were conducted in a relatively “ideal” environment that maximized safety and productivity. The platforms provided stable decks in water depths in excess of 350 m. There was ample room for equipment and electricity to run equipment. Emergency evacuation by helicopter was available at all sites and sea-to-land communication networks were well established. Below water, the platform structures provided opportunities to stage equipment such as extra gas bottles for emergency use. Down lines for decompression were stationary, not subject to the pitch and roll of a support vessel. And, the platform owners helped underwrite the cost of these expeditions.

The CCS teams utilized trimix and deep air decompression technology on these platform-based projects. All dives were made with scuba technology. To support emergency first aid needs a recompression chamber was installed on site.

All existing deep diving technologies can be applied to scientific explorations. Each project must be evaluated to determine which technology best suits that specific need. Available funding, location, team experience, and emergency response infrastructure must be considered.

Administrative Protocols

Most scientific divers are scientists and students associated with universities and resource managers employed by government agencies. Following OSHA exemptions for "scientific diving" these institutions and agencies rely upon the American Academy of Underwater Sciences to set standards and provide the administrative/legal foundation for the application of diving technologies to the pursuit of scientific objectives. Deep diving (>50 m) will require those responsible for institutional risk management to re-evaluate the institutional position on scientific diving. Universities will be particularly sensitive to these new risks due to the nature of the clientele they serve, primarily young students. Scientists and dive officers will face added responsibilities relative to the increased risks inherent in deep diving.

Standards

The scientific diving community and those institutions/agencies supporting scientific diving look to the American Academy of Underwater Sciences (AAUS) to establish standards for training, safety, and project implementation. "Scientific diving" is a unique form of professional diving. Purposes and objectives vary significantly from those of military, commercial, and recreational diving enterprises. Hence, standards must reflect this uniqueness and provide the diving scientist options to achieve the project objectives within the boundaries of funding, team experience, and established acceptable risk.

The AAUS is an organization run by the clientele it serves; the diving scientist, student, and supporting institution. In the process of establishing standards for deep diving opinions and debates will cover the spectrum from being too conservative to being too lax. As a supporting professional organization with a critical mission and responsibility in the advancement of diving technology as a tool to scientific discovery, the AAUS must embrace standards that adequately serve the need for risk management without stifling scientific productivity, or worse, forcing the diving scientist into a renegade operating protocol. On the other hand, the diving scientist must recognize and accept the need for standards suitable for the activity and increased risks.

Procedures

All diving is technical and deep diving requires the application of increased levels of specialized technology. To utilize these technologies, procedures unique to deep diving will have to be employed. Project scientists and dive officers need to be aware of this and committed to accepting procedures that minimize risk factors.

Deep diving will require more training for the divers and expanded surface support teams. Equipment not normally employed by scientists on shallow water projects (<50 m) such as gas mixing equipment, rebreathers, diver tracking electronics, wireless communication equipment, and recompression chambers will be necessary. The technology and skills of diving will necessarily become a primary focus, more so than in the application of standard (*i.e.,* recreationally based) scuba technology to scientific missions. Equipment maintenance between scientific missions will require expanded effort and funding. And, paperwork to track training, experience, and equipment maintenance will also increase.

Experience

Experience in deep diving is a critical factor. Relatively few of those involved in scientific diving are experienced at deep diving. Research and scientific diving involves a broad spectrum of practitioners, male, female, young, old, mature, and not so mature. The academic institutional setting strives to be non-restrictive, and scientists, who are often faculty members as well, are pressed to involve individuals who may not be suited to deep diving activities. Hence, standards for training and experience must be codified to provide dive officers and principal investigators a framework for excluding unsuitable candidates while staying off the slippery slope of "discrimination."

It is not likely that every academic institution can or will maintain the necessary core of experienced deep divers and specialized equipment necessary to routinely carry out deep diving projects. And often, there is a significant down time between deep diving projects during which the challenge will be to maintain skill proficiency and equipment condition. In the university system, students trained in deep diving technology graduate, leaving gaps in the team. The research community must develop mechanisms to share personnel and equipment. Programs such as the National Undersea Research Program must be maintained as a source of experience, equipment, and funding support.

Funding

Projects involving deep diving technology will be more costly by several orders of magnitude. Specialized equipment, more equipment, more surface-support personnel, increased emergency response infrastructure, higher levels of training, etc., will drive up the cost of projects. Funding agencies such as the National Science Foundation will have to recognize and accept the reality of greater cost for deep diving projects, as will the supporting academic institutions and resource management agencies. Legislative bodies will need to be informed and convinced of the value of programs such as the National Undersea Research Program, which can and should be a major driver in the advancement and application of deep diving technology.

On a cautionary note, university scientists and students are famous for finding ways to accomplish research objectives on a shoestring budget. However, in the application of deep diving technology, this ingenuity could be a liability if safety is compromised to stay within budget. It is the responsibility of the deep diving scientist to educate the funders and press the need for adequate funding to carry out deep diving missions that stay within established acceptable risk boundaries. Dive officers and diving control boards will need to be vigilant and disciplined in controlling deep diving projects.

Conclusion

The application of deep diving technology to scientific missions will greatly advance our understanding of aquatic ecosystems. This technology can and should be applied to scientific missions. However, it must be done within boundaries of acceptable risk. Dive officers, scientists, institutional administrators, funding agencies, and the American Academy of Underwater Sciences must all recognize the unique challenges involved in deep diving and accept the responsibility for applying deep diving technology in a manner that minimizes risk. Standards and procedures must be developed and codified that recognize the uniqueness of scientific diving and provide the practitioners of deep diving an administrative/legal platform from which to operate. Funding must be adequate to apply advanced deep diving technology in a manner that ensures that the projects occur within the boundaries of acceptable risk.

Programs such as the National Undersea Research Program should be supported and enhanced as a leader in the development and implementation of advanced diving technologies.

MIXED-GAS CLOSED-CIRCUIT REBREATHERS: AN OVERVIEW OF USE IN SPORT DIVING AND APPLICATION TO DEEP SCIENTIFIC DIVING

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Introduction

Closed-circuit rebreather (CCR) use is on the rise in the sport diving and scientific diving communities. At least four major manufacturers displayed one or more CCRs and at least two semi-closed circuit rebreathers (SCRs) at the 2005 DEMA Show in Las Vegas. There were some lesser known players also showing both CCRs and SCRs.

CCRs are not new to scientific diving. CCR use by scientific divers, while not as typical as open-circuit diving, has been common for more than 30 years. As just one example, as early as 1969, the Tektite underwater habitat projects equipped aquanaut scientists with both open-circuit and CCR scuba (Earle and Giddings, 1980).

CCRs are relatively new to sport diving. Although the Electrolung was offered to the sport community as the first commercially available mixed gas CCR in 1969, it was off the market by 1971. During its short tenure, it had some following with commercial, military, and scientific divers, but little sport market penetration (Starck, 1993). The testing of the CisLunar Mark I rebreather by Dr. William Stone in the 1987 Wakulla Project was likely the beginning of a trend that has propelled CCRs into sport diving, as well as setting the stage for tec diving in general (PADI, 2005; Stone, 1989). Following up on his earlier studies and technological development, in 1999 Stone's dive team used the CisLunar Mark V (fifth generation version of his unit) for extensive cave exploration in the 270- to 300-foot depth range in the Wakulla 2 project (Protec Diving, 2005).

While CCRs aren't new to scientific diving, the rise of CCRs in sport diving may offer new opportunities for scientific diving with respect to improved capabilities through technology advancement and cost advantages due to manufacturer competition and economies of scale in production. This paper overviews: 1) the technology and its advantages and disadvantages as a deep scientific diving capability; 2) the limited sport diver CCR incidence data (especially deeper diving); 3) drawn conclusions with respect to training and operational recommendations that may apply to deep scientific diving; and, 4) two examples of CCR use for scientific deep diving.

Closed-Circuit Technologies Overview

Although there are many variations in design and details, rebreathers are broadly classified as fully-closed oxygen rebreathers, semi-closed mixed-gas rebreathers and fully-closed mixed-gas breathers. What they all have in common is that they reclaim some or all of the diver's exhaled gases for reuse after removing carbon dioxide and replacing consumed oxygen (Bozanic, 2002). The benefit of this is more effective use of the gas supply when compared to conventional open-circuit diving, which simply exhausts exhaled gases.

Rebreathers cycle gases through the *breathing loop*. The breathing loop includes a counterlung, which expands and contracts when the diver exhales and inhales, an absorbent canister, which contains a chemical for absorbing carbon dioxide, and one or two high-pressure cylinders that provide inert gas and/or oxygen as needed. One-way valves assure that gases cycle properly as the diver breathes (PADI, 2005; Bozanic 2002).

Oxygen Rebreathers

Due to the depth restrictions related to using pure oxygen (6m/20ft) fully-closed oxygen rebreathers lie outside the scope of deep scientific diving, though they certainly may have some benefit for shallow water applications.

Semiclosed Rebreathers (SCRs)

SCRs reuse part of a diver's exhaled gases. Units classified as constant mass-flow and keyed-RMV SCRs inject a steady stream of a single gas mix, enriched air nitrox, trimix, or heliox (depending upon the planned depth) into the breathing loop. At the same time, a valve allows a steady stream of gas to exhaust from the breathing loop. This replenishes consumed oxygen as the diver's exhaled breath goes through loop, with the scrubber removing carbon dioxide and the steady exhaust keeping inert gas from building up disproportionately. Because the diver consumes the oxygen, the fraction of oxygen in the breathing loop is lower than the supply gas. The gas composition in the loop can be determined reasonably accurately with simple formulas based on the supply flow rate and the diver's activity, though a preferred means is to have an oxygen sensor that displays the oxygen percentage (Bozanic, 2002; PADI, 2005; Thalmann, 1996).

Palmer (1993) described the primary advantages of the semi-closed system as comparatively low cost, mechanical simplicity, and gas efficiency typically equal to one third the gas requirements of open-circuit comparable dives. The primary drawbacks (compared to CCRs) are that a given gas mix has a much narrower range. Also, the oxygen content cannot be varied to optimize decompression. Rather, SCR decompression is similar to open-circuit decompression using enriched air nitrox (Bozanic, 2002).

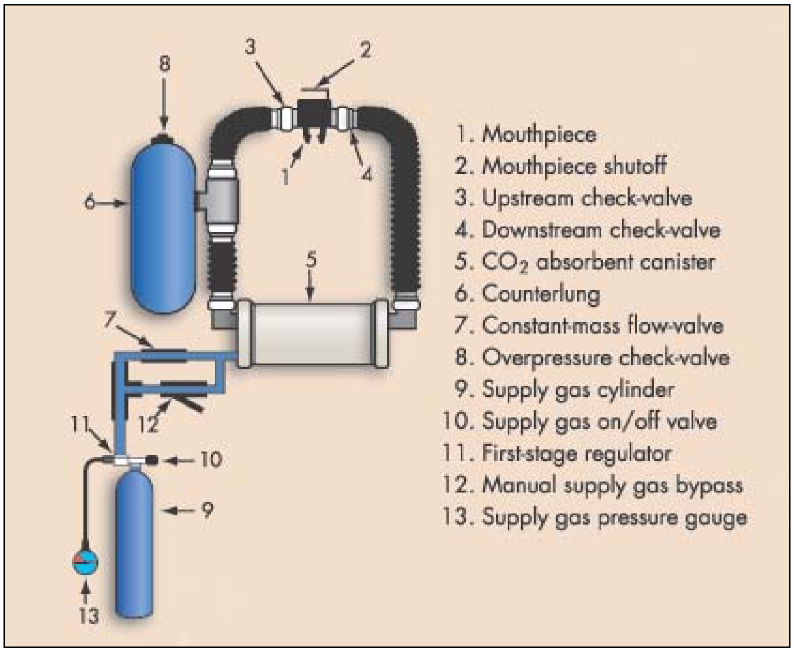


Figure 1. Conceptual schematic of constant mass SCR. Copyright PADI 2005, reprinted with permission.

In watching the market and through interaction with the dive community, it is the authors' perception that semi-closed circuit use is at best level in the sport market, driven primarily by novelty and curiosity. With respect to serious deep diving, CCRs are the growing trend for advantages that will become apparent in the following discussion, but it should be noted that SCRs have been used for dives approaching the 300 foot range (Thalmann, 1996; Bozanic, 2002). However, this does not appear to be the trend in either sport or scientific deep diving, so the focus here is appropriately placed on the CCR.

Closed Circuit Rebreathers (CCRs)

The modern mixed-gas CCR feeds a closed breathing loop (no exhaust except to accommodate depth/volume changes) with a supply of diluent (air, enriched air nitrox, trimix or heliox) with a relatively low fraction of oxygen, and pure oxygen. The diluent supplies the breathing loop with volume and inert gas. The oxygen supply replaces the oxygen consumed from the breathing loop. The diluent's small fraction of oxygen also provides some oxygen, but it is primarily there as a safety precaution. It reduces the risk of a diver accidentally having pure inert gas in the breathing loop, and makes the diluent supply available as an open-circuit bailout gas source (PADI, 2005; Bozanic, 2002; Graves; pers.comm; Readey, pers. comm.)

Before the dive, the unit is set for an oxygen partial pressure *set point* (usually from .7 to 1.2 ata) that is monitored by oxygen sensors in contact with gas in the breathing loop (typically there are three for reliability). Onboard electronics add oxygen from the oxygen cylinder via a solenoid activated valve based on the sensor readings. With most units, the diver manually adds diluent to maintain volume during descent, and manually releases gas from the loop to reduce volume during ascent. Most units also have valves that add diluent if the loop volume drops below a certain point, or release gas from the loop if it is too high (similar to a dry suit exhaust valve). CCRs provide secondary displays showing the oxygen sensor readings and have oxygen bypass valves, permitting the diver to manually control the unit in case of electronics failure or some need to override the settings (PADI, 2005; Bozanic, 2002).

The primary advantages of CCRs are that they are the most gas efficient UBAs, and that they optimize decompression by allowing the maximum possible oxygen (within exposure limits) at all stop levels. Both advantages result in extended depth capability compared to open-circuit and semi-closed circuit scuba. The primary disadvantages are cost (compared to open- and semi-closed circuit scuba), relative complexity of training, and greater effort/time in setup, tear down and maintenance (PADI, 2005; Bozanic, 2002; Pyle, 1996). The use of electronics and relative fragility of the oxygen sensors raises the potential for failures, though redundant design and manual override options manage the safety issues with respect to such failures. This not only gives many CCRs a high degree of dive survivability after a failure, but even mission survivability for many types of failure (Thalmann, 1996; Stone, 1989; Steam Machines, 2003; Graves, pers. comm; Readey, pers. comm.)

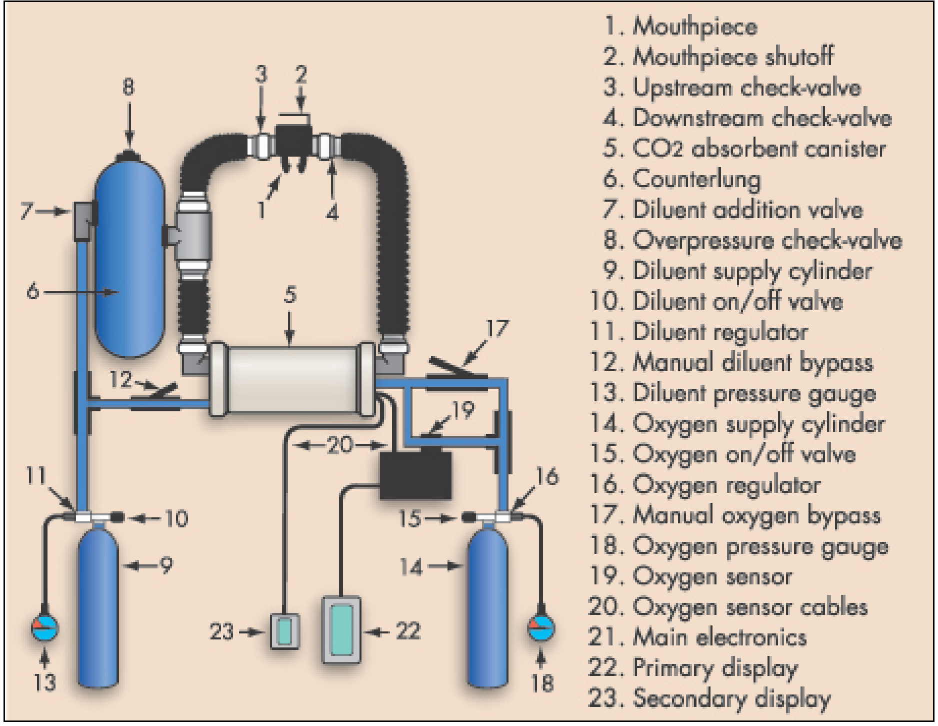


Figure 2. Conceptual schematic of mixed gas CCR. Copyright PADI 2005, reprinted with permission.

CCRs in Deep Diving.

There are specific requirements for using a CCR for deep, decompression helium diving. The first is that only a CCR designed and recommended for this purpose should be used (Bozanic, 2002). Beyond this and the training/experience requirements (discussed later), in general the technical/logistical requirements involve gas choice and backup/bailout requirements.

The diluent gas is usually either heliox or trimix, with the oxygen fraction based on being low enough that the PO_2 at maximum would be equal to or less than the oxygen set point. This may mean the diluent gas would not support the diver at the surface, adding a variable to be addressed in planning and emergency procedures. As an example, if the set point were 1.0, a dive to 300 ft would require a diluent of no more than 10% oxygen, and even less if a lower set point were used (Stone, 1989; Graves, pers. comm; Readey, pers. comm.) Due to CCR efficiency, trimix does not offer a substantial cost advantage over heliox, though many in the sport community appear to favor trimix. This may be due, at least in part, to comfort and familiarity with it in open-circuit deep tec diving.

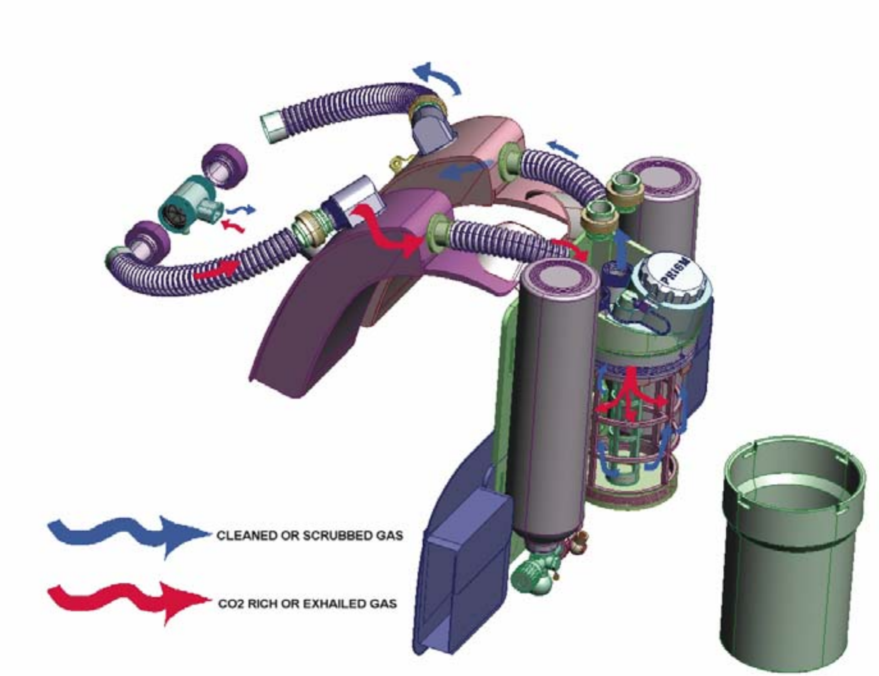


Figure 3. PRISM Topaz CCR diagram shows that reality is more complex than theory. Copyright Steam Machines Inc., reprinted with permission.

Back up is a major logistical issue because except for very short exposures, it is difficult or impossible to carry sufficient backup decompression gas supplies for an open-circuit bailout. However, it is important that each diver have a method for safely aborting a dive and completing decompression, even after a catastrophic (not recoverable) CCR failure.

For deep open-water CCR diving, Pyle (1996) generally advocates systems (specifics vary to accommodate whether the dive is at a single station, over a wider area, etc.) in which each diver carries sufficient diluent and oxygen to reach a larger, surface-deployed bailout system. Divers send up an emergency signal float in the event of a catastrophic CCR failure. The surface-support team deploys a surface-supplied open-circuit system that delivers enriched air nitrox and oxygen with more than sufficient gas to allow the diver(s) to adequately decompress.

Another backup approach is to have a second CCR available, although Pyle (1996) feels that this has logistical difficulties in many circumstances. Nonetheless, the Wakulla 2 project used this approach for the cave explorers, with a backup CisLunar Mark V mounted on the divers' scooters and, in some instances, by combining two CisLunar Mark Vs into a single unit on the diver's back (Protec Diving, 2005). Since the exploration divers decompressed in a commercial diving personal transfer capsule (PTC), the secondary Mark V was apparently intended as back up to exit safely from the cave, but not for decompression. More recently, a scientific dive team in the Indo-Pacific region has been working in the 400-500 fsw range. This team uses one back up CCR per diver because open circuit is insufficient at the those depths (Readey, pers. comm.)

CCR Cost Effectiveness

From a science diving point of view, with respect to diving with helium in the 300+ foot range, simple analyses show that CCRs are significantly more cost effective than any form of open-circuit diving (umbilical or scuba). A comparison of just the helium use on the bottom portion of a dive illustrates this clearly.

For a square dive to 330 feet (approx 10 ata) for 40 minutes, a typical rebreather will require approximately 2.5 cubic feet of diluent to maintain counterlung volume on descent. Assuming the use of trimix with 60% helium, that's 1.5 cubic feet of helium, which does not change regardless of workload. Assuming no depth changes or gas waste from the loop, that's less than $3 in helium costs.

More realistically, a dive would be made with a full cylinder of diluent (for bailout reasons among others). In this case, a typical 30 cf supply cylinder requires 18 cf of helium to produce a 60% helium diluent. For bailout purposes, however, a diver will typically have more diluent and oxygen. Pyle (1996), for example, cites 80 cf of diluent (48 cf helium) as typical for his deep operations to provide adequate open-circuit bailout to reach emergency breathing equipment.

Even 48 cf is far less than what open-circuit systems use on deep dives. Based on decompression using the least conservative Abyss decompression software, a diver with a light-moderate at work breathing rate using open-circuit UBA (any form) for a 330 foot dive for 40 minutes with 60% helium trimix would consume about 270 cf helium. This does not include the helium required for reserve, nor used during decompression.

See Table One for a comparison of gas use for the same dive and decompression. Note that while this is well within the capabilities of a CCR as a self-contained dive, the gas requirements make such a dive with open-circuit scuba logistically difficult as well as much more expensive. The differences between open-circuit and closed-circuit gas costs and feasibility become increasingly apparent as depth and/or time increases, though gas cost difference is less of an issue with commercial diving with gas reclaim systems, which can recover 85 to 95 percent of the helium (Gernhardt and Lambertsen; 2004).

Table 1. CCR versus open-circuit gas use on 330 ft/40 min dive.

Assumes open circuit decompression carried out with TMx9/60, EANx36, EANx50 and oxygen. All calculations based on an RMV surface of .75 cfm and decompression using Abyss 100 algorithm.

	CCR	Open Circuit
Helium	1.5 cf (18 cf to fill cylinder)	180 cf (min) + 90 cf reserve
Oxygen	9 to 14 cf (30 cf to fill cylinder)	111 cf (min) + 56 cf reserve*

*Assumes EANx blended with air and oxygen.

During a series of inwater trials comparing deep mixed-gas open-circuit scuba to deep mixed gas CCR diving, Parrish and Pyle (2002) found dramatic differences in both the logistical and consumptive rates. Their findings are that open-circuit systems required seven times more preparation time and consumed 17 times as much gas. Decompression was 42 to 70 percent longer with open circuit.

When compared to open circuit, another cost/logistical advantage of a CCR as deep diving life support system is greater support vessel choice and flexibility. This is because a CCR operation would typically require fewer cylinders for the same dive (NOAA, 2001).

Sport divers have taken rebreathers very deep. As reported in multiple print and web news reports (divernet.com and theage.com.au, among others), one of the most famous cases is Australian David Shaw, who twice descended to 270 m (890 ft) in South Africa. On his first dive he found the remains of a diver who attempted the dive with open circuit, then perished on a second dive attempting to recover those remains. While dives to this depth still appear to be quite hazardous with at least some versions of existing CCR technology, dives to 400 fsw have become common and do not appear unreasonable for properly qualified (trained and experienced) individuals with appropriate CCRs, backup, and support.

CCR Deep Diving Disadvantages.

Although CCRs outperform open circuit in deep diving in many respects, they do have downsides. The first is that they require more time in predive and postdive care compared to open-circuit systems (PADI, 2005; Steam Machines, 1997-2005), though total predive prep may be less for a deep mixed-gas diver (Parrish and Pyle, 2002).

A second issue is that many problems with CCRs are not immediately obvious and can cause a diver to lose consciousness without warning if the diver fails to detect the problem through alert monitoring of instrumentation. By contrast, open-circuit failures are usually dramatic and obvious. Counterbalancing this somewhat, however, is that a diver who notes a CCR problem quickly typically has more time (a couple of minutes) to sort out the problem than does an open-circuit scuba diver because it takes time to diminish oxygen in the breathing loop to critical limits (Pyle, 1996; Readey, pers. comm; Graves, pers. comm; PADI, 2005).

A third problem is that a CCR's capabilities bring with it a potential for a deep diving decompression disaster in an untrained diver. Because CCR gas use is largely independent of depth, there's nothing preventing a diver from creating a decompression obligation that the CCR may not be able to support (Readey, pers. comm.) For example, Abyss software's least conservative algorithm predicts about 10 hours decompression time for a 90 minute dive to 350 ft using TMx9/60. The bottom portion of this dive is easily within the capabilities of several CCRs, but the decompression is outside what most can do (without additional systems and support).

A fourth issue is that diving CCRs is relatively easy when everything works, creating a deceptive simplicity for divers not adequately trained in managing contingencies. Many CCRs can fully get a diver back to the surface without going to a bailout system through manual operation, even in the event of partially flooded breathing loops, oxygen sensor failures, or complete failure of the primary electronics. But, manual operation requires practice, discipline and strong familiarity with CCR theory and design (Pyle, 1996; Graves, pers. comm.)

These drawbacks point to a significant issue with respect to scientific diving. In deep decompression diving, all divers using CCRs must have a high degree of training and experience. At their present state of development, a prevailing opinion is that it's not reasonable to allow under-qualified individuals to make such dives under the supervision of highly qualified individuals watching over them (Graves, pers. comm; Readey, pers. comm.) This may mean that some primary investigators will be unqualified to make dives required for their research, requiring them to rely on appropriately qualified scientific CCR divers to act as their eyes and ears. Situations requiring taking relatively less qualified divers to deep depths with close supervision, at present, require something other than the CCR approach.

Finally, it's worth noting that while CCRs are more cost effective with respect to gas use than open circuit on deep dives (especially those using helium without reclaim), the initial costs of training, the hardware and its upkeep are higher than open-circuit scuba, though not as high as commercial-type open circuit UBA. However, if deep diving with helium is a frequent operational requirement, CCRs generally end up being the most cost effective way to make such dives.

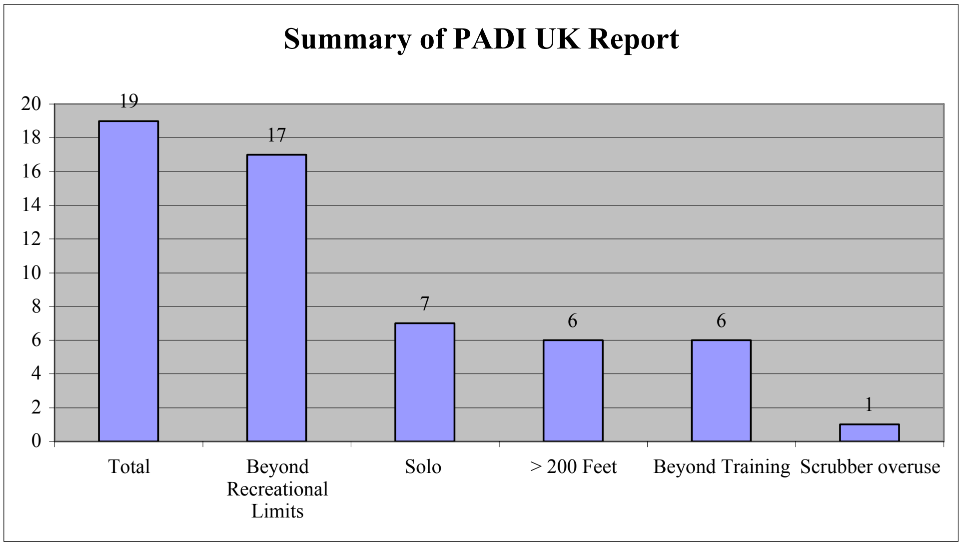
CCR/SCR Incidents in Sport Diving

Closed-circuit scuba is a rising but still relatively small of the sport diving community. Therefore, the number of incidents on file is comparatively small as well. The following summarizes existing closed-circuit scuba incidents (including semi-closed) and market penetration as determined by PADI International Ltd., PADI Americas and the Divers Alert Network. Incidents may overlap in these reports, so they must be treated individually, though we can draw some conclusions from them together. In addition, Kevin Gurr of Closed Circuit Research Ltd. provided an analysis of CCR incidents, though he didn't provide the source, number, and specifics of the incidents analyzed. Given the very limited quantifiable data available, this paper considers some anecdotal reports and qualitative comments from the field that may be relevant.

PADI International Ltd.

Caney (2005) derived the following estimates for January 1998 to January 2005. His estimates were that 1000-3000 sport divers train in CCRs annually (report excluded semi-closed rebreathers). He estimated approximately 5000 Inspiration CCRs and 200 PRISM Topaz CCRs sold up to January 2005. He reported data on 28 CCR fatalities among civilians, 19 of those with sufficient data to report details:

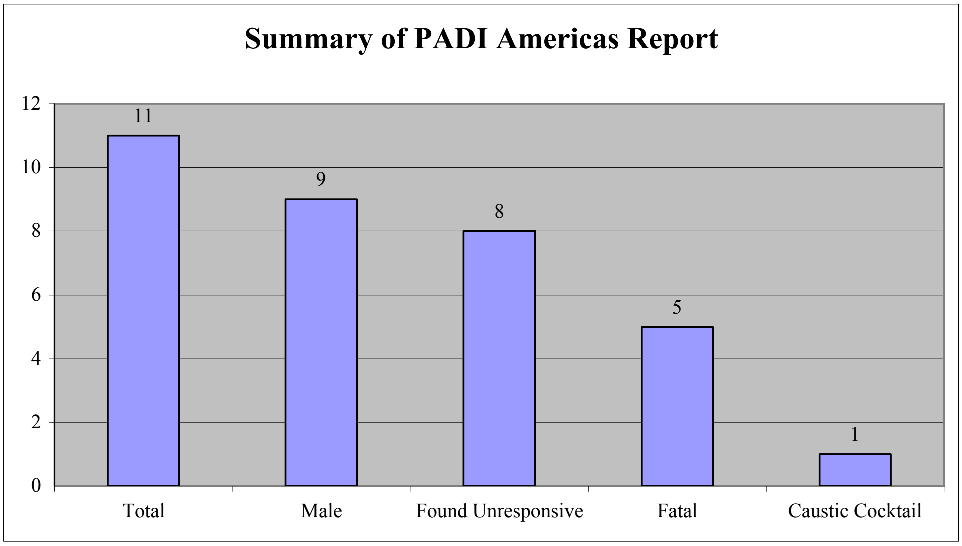
- Seventeen of the 19 occurred beyond recreational limits (130 ft, no-stop, open-water diving).
- Six involved dives deeper than 200 ft and seven were diving solo.
- At least six were well beyond the scope of their training.
- At least one case appears to have involved overuse of the carbon dioxide scrubber.



PADI Americas

For the period of 2001 through 2005, PADI Americas has data on 11 CCR and SCR incidents (PADI, 2006):

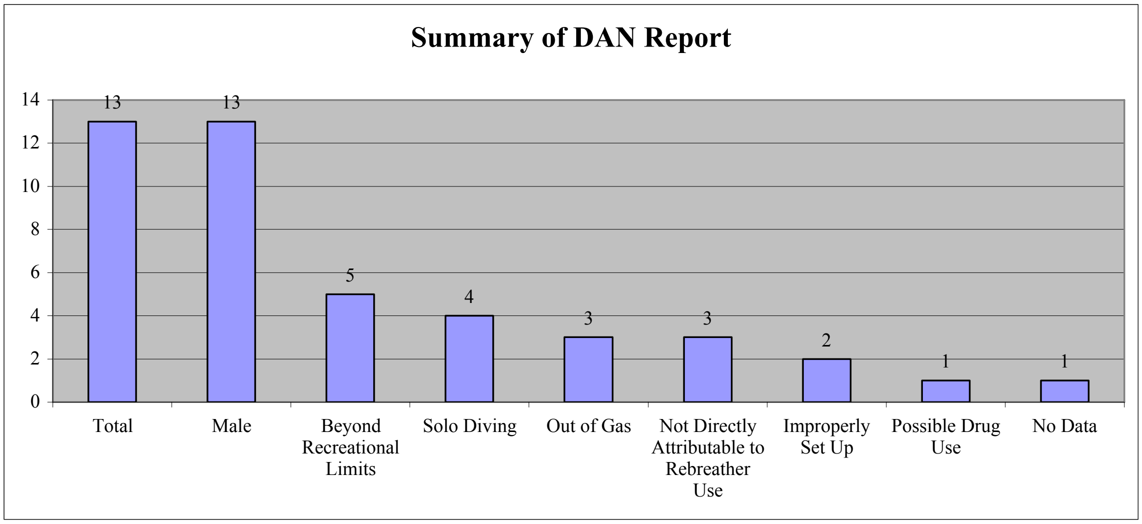
- Five of the 11 incidents were fatal.
- Nine of the victims were male, two were female.
- One incident was a physical injury (dislocated shoulder) not directly related to using a CCR/SCR.
- Eight incidents, including all of the fatal accidents, involved the victim becoming unresponsive or being found unresponsive underwater or in the water.
- One incident involved a “caustic cocktail” (water in the breathing loop bringing CO_2 absorbent chemicals to the diver’s mouth)



Divers Alert Network

DAN (Denoble, 2006) reports 13 fatal CCR/SCR incidents for the period of 1989-2003 for which they have data:

- All 13 of the victims were male.
- Five of the cases involved diving beyond recreational limits.
- Three cases were not directly attributable to the use of a rebreather, and included omitted decompression due to dry suit blow up, possible shark attack, and a probable cardiac arrest.
- One case may have had drug use as a contributing factor.
- In one case the body was never recovered, and there are no data upon which to infer a cause.
- Four cases involved solo diving
- Three cases involved the unit being out of gas. One of these led to omitting significant decompression, leading to a fatality. The data aren't specific as to whether a CCR or an SCR was used. A constant-mass SCR with an open supply cylinder will continue to flow and eventually exhaust itself. Therefore, without more specific information, the exhausted supply cylinders listed in the other two cases are not necessarily causative or contributory.
- Two cases involved improperly set up units.
- One case involved solo diving to test a homemade unit (built from a kit) that had recent technical difficulties.



Closed Circuit Research Ltd.

Closed Circuit Research Ltd.(2005) cites the following review of CCR incidents as pivotal in designing their Ouroboros CCR. They did not provide quantified data with frequency or numbers:

- Divers started the dive with their electronic control system off.
- Divers started the dive with their oxygen turned off.
- Divers descended with diluent off and then panicked when they could not find the manual addition.
- Divers did surface swims on hypoxic diluents.
- Divers did not pack the absorbent canister correctly or the design of the canister allowed CO_2 to bypass if O rings where incorrectly greased or assembled.
- With insufficient guidance on canister durations, people exceeded the duration limits.
- Temporary floods made the breathing loop unusable.
- Insufficient filtering produced oxygen solenoid and ADV failures.
- Rubber hose attachment systems produced stress points [that damaged] the hoses.
- Electronics in the loop [were] affected by moisture.
- Gas supplies were accidentally switched off.
- Failures in the electronics made the unit unusable.
- Divers become stressed at high work rates and the Human Computer Interface (HCI) became confused.
- DCI [sic] occurred as a result of the unit's inability to maintain a near constant PO_2.
- Divers did not follow pre-dive procedures.

Anecdotal Reports and Comments.

Although the data are limited, both authors have heard numerous anecdotes related to SCRs and CCRs from use in the field. While basing conclusions on a single incident or report requires caution and care, intuitively some of these prove quite useful. As an example, the experiences of Pyle (1996) are well documented and reasoned lessons appropriate for anyone interested in deep mixed-gas CCR diving. Other reports and anecodotal incidents reported to the authors cannot be quantified, but should at least be noted from a cautionary standpoint:

- At least one model of CCR could be put into calibrate mode at depth (this process injects the counterlung with pure oxygen); this has reportedly been corrected, though anecdotes cite it happening several times when the model first entered the civilian market.
- Improper packing of the CO_2 absorbent is frequently reported.
- Incident data summaries are likely to be incomplete and post incident analyses not always accurate (Readey, pers. comm.) This could be attributed to many factors, including but not limited to, manufacturer propriety in litigious regions, gaps in reporting procedures, and accident investigators who lack familiarity with the technology.
- It's a commonly reported perception that civilian CCR divers purchase mixed-gas CCR units, yet end up not diving with them very much. Estimates vary on what proportion of civilian CCRs end up in disuse, and disuse may vary with make/model. This calls into question any conclusions as to CCR incident trends derived from activity estimates based upon units sold.
- A commonly reported perception is that highly experienced open-circuit tec divers have completed CCR training and start making CCR tec dives (deep/decompression) without accumulating much experience with CCRs in the no-stop envelope.

Lessons and Conclusions

Existing incident data are, at present, too small and fragmented to determine statistically useful trends. Furthermore, there are few data about exactly how much civilian CCR and SCR diving is actually taking place. Sport diving currently lacks the means to estimate with reasonably high accuracy the active participants, number of dives, and number of hours for civilian CCR use. Nonetheless, the limited data available provide lessons and conclusions upon which to base recommendations applicable to both sport and scientific diving with respect to design, procedures, and training.

1. The limited data show a trend toward a rising number of incidents in which the victim was using a CCR/SCR. Based on the growing availability and attention to these technologies, one can reasonably induce that this at least partially reflects a rise in their use. Furthermore, in assessing incidents and determining trends, it's important to discriminate between incidents in which the use of a CCR/SCR was causative or substantially contributory and those in which it just happened to be the UBA in use. Similarly, as diving learns from experience, incidents that happened four or five years ago may be impossible or unlikely today due to compensating changes in design, procedures and/or training. Speaking broadly, there are not enough data to conclude that CCR/SCR divers have a disproportionate number of incidents, nor are there any indicators that suggest so.

2. Deep diving and diving beyond recreational limits appear frequently in the reports. The data do not provide sufficient information to analyze the experience and training these divers had before moving into tec diving with a CCR, although this was cited in the PADI UK report (Caney 2005). Statistically, in any mode of diving, deep diving has more risks than shallow no-stop diving, so it would be expected to appear in the incident data more frequently. It's noteworthy that the PRISM Topaz has, to date, no fatalities and few incidents attributed to divers using it, irrespective of depth. As may be expected, the manufacturer attributes this to design, but also credits their training requirements, which include a minimum of 100 hours of no-stop diving shallower than 130 feet before the diver may enter tec training or instructor (for no-stop use) training with the unit (Readey, pers. comm.) Gurr (2005), with extensive experience with both CisLunar and Closed Circuit Research Ltd. rebreather use and development, states that 50-100 hours CCR no-stop diving is a reasonable minimum experience before moving into helium-based decompression deep diving with a CCR. This lines up well with Pyle's (1996) experience and recommendations: "After my first 10 hours on a rebreather, I was a real expert. Another 40 hours of dive time later, I considered myself a novice. When I had completed about 100 hours of rebreather diving, I realized I was only a beginner. Now that I have spent more than 200 hours diving on a closed-circuit system, it is clear that I am still a rebreather weenie." Pyle goes on to say that it takes a "fair amount" of experience for a CCR diver to know his limitations.

   Based on what we know, it would seem that regardless of a diver's open-circuit experience, a minimum of 50-100 hours CCR experience in the no-stop envelope appears to be a reasonable prerequisite before making helium gas decompression deep dives below 130 feet. Current AAUS standards concur, requiring 25 hours no-stop experience prior to training to make decompression dives, and 50 hours prior to training to dive with an inert gas other than nitrogen (AAUS, 2005)

3. Human error appears commonly as a cause of CCR accidents (as it is with all diving incidents). Human error can only be handled two ways: engineer them out, or train/procedure them out.

   Some reported incidents appear readily engineered out. A few examples include: The PRISM Topaz must be disassembled to access the calibration mode, making it impossible to go into calibration mode underwater (Steam Machines, Inc., 1997-2005). The Drager Dolphin SCR uses color codings on the hoses and components to guide the diver in correct unit assembly (Drager, 1997). The Ouroboros Rebreather absorbent canister was designed so that it mechanically reduces packing errors (Closed Circuit Research Lt., 2005). A reasonable conclusion is that CCR design and selection should include an eye toward eliminating human errors through engineering to the degree possible.

   Human error that you cannot engineer out must be handled with training and procedures. While CCRs use extensive checklists for pre-dive and post-dive procedures (Closed Circuit Research Lt., 2005; Steam Machines, Inc., 1997-2005), ultimately it's up to the diver to follow them. Pyle (1996) notes that discipline is the most important quality a CCR diver must have. A reasonable conclusion is that CCRs should have detailed pre- and post-dive checklists, and training should emphasize repeated use of these lists. The Ouroboros Rebreather goes so far as to have the predive checklist built into the electronics, forcing the user to go through it prior to diving (Closed Circuit Research Lt., 2005). Human error during the dive must also be trained out. Although human factor prompts such as flashing lights and vibrating mouthpieces can help alert a CCR diver to a problem requiring attention (Gurr, 2005; Readey, pers. comm.), ultimately it is the diver who must recognize a problem, determine a solution, and act accordingly. Pyle (1996) recommends that CCR training emphasize failure detection, manual control, and bailout.

Supporting Readey's assertion that training is part of the reason for the PRISM Topaz's excellent safety, the authors found that training for it emphasized manual control so much that after completing training, they felt considerable discomfort with allowing the unit to work automatically.

The benefit, of course, is that the authors can dive the unit with the primary electronics totally dead, if necessary. Indeed, during pool training one unit had multiple system problems (intentionally), yet it was possible to continue the dive by enacting various emergency procedures and manual control. Beyond this, flying a unit manually develops the habit of constant attention to PO_2 gauges, as well as automaticity with manually controlling oxygen and diluent. Apparently, many PRISM Topaz divers prefer to dive the unit primarily manually, allowing the automatic system to control (with close attention to warning devices) only when task loading precludes it (Graves, pers. comm.)

It is reasonable to conclude that CCR training that does not emphasize disciplined use of pre/post dive procedures, attention to gauges during a dive, and manual operation is not likely to be adequate, at least for the purposes of deep decompression diving.

4. Solo diving appears in the reports several times. There are insufficient data to determine whether solo diving is at all contributory to accidents because it may be that CCR/SCR divers commonly dive solo due to the relative lack of rebreathers in the overall dive community. Nonetheless, without further information it is reasonable to at least be wary about solo diving. One case in which solo diving was possibly a contributing factor was the one in the DAN data in which the diver was testing a closed-circuit system known to have problems. This diver had no one to assist him in the event of continuing problems with the unit.

   Also arguing against solo diving, team diving with CCRs has demonstrable safety benefits. In their own training with the PRISM Topaz, the authors found that teammates remind each other of basic procedures and gauge checks throughout the entire dive process, adding to overall safety. The Ouroboros Rebreather has a large, rear-mounted PO_2 gauge that allows divers to confirm each other's oxygen levels (Closed Circuit Research Lt., 2005.) This feature was originally intended for training units, but has been so popular that it is now standard (Gurr, 2005). This also points to team diving practices as contributing to risk reduction and management.

5. Some incidents and anecdotes suggest that some divers use CCRs beyond the intended depths for which specific models are rated and tested. It is likely that this has contributed to incidents, some of which may not be included in the incident data (Readey, pers. comm; Gurr, 2005; Graves, pers. comm.)

   Readey, who has been involved with CCR development and use for more than 30 years, makes an interesting observation involved with equipping and training scientific divers for deep CCR use. He suggests that the idea is to become familiar with CCR operation and design before selecting a unit. Readey says that often a diver chooses a CCR before the individual has sufficient information to discriminate between the performance and operational differences. The result is often either a need to entirely reequip and retrain, or to proceed with a unit that is less than optimum for the intended use.

   A related issue is the CE mark, which many in the sport community think of as a safety approval. Mike Harwood of the UK Health and Safety Executive said this during Rebreather Forum 2.0 (Menduno, 1996): "I just want to lift the veil on this CE-mark that everybody hears about, because a lot of people seem to think the CE-mark means it's safe. [Nonsense]. It's a conformity assessment standard."

   Readey observes that a CE-mark means you're able to reproduce your product as it was designed to very close tolerances, but it doesn't necessarily mean the design is good. "A CE-mark can mean nothing more than you're very good at replicating a very poor design."

Two Examples of Deep CCR Use in Scientific Diving

Scientific diving to 300 fsw and deeper with CCRs is relatively rare. For one reason, it is prohibited or significantly restricted by the guidelines of U.S.-based (and other) scientific diving organizations and institutions (AAUS, 2005; NOAA, 2001). Nonetheless, it is getting growing attention due to the cost and logistical advantages the technology offers for deep diving. Two examples of operations using CCRs for deep scientific diving are provided.

Richard Pyle, PhD

Cited extensively for his expertise in this paper, the authors and most of the dive community know Richard Pyle of Bishop Museum, Hawaii, to be one of the pioneers of deep CCR scientific diving operations. Pyle explores coral reefs and collects fish specimens in the 200 fsw to the 400+ fsw range. He began using open-circuit trimix in the early 1990s, and switched to CisLunar Mark IV CCRs in 1994.

Although his current methodologies have likely evolved, in the 1990s (Pyle, 1996) Pyle conducts his operations with CisLunar mixed-gas CCRs, backed by surface support and staged open-circuit emergency decompression gases. Pyle has documented his methodologies extensively. Given that they're built on hundreds of hours of experience, the authors recommend his papers and refer interested readers to them for detail.

Indo Pacific Deep Science Team

At this writing, there is a team making extensive, repetitive deep mixed-gas dives using the PRISM Topaz for the purposes of collecting fish species, similar to Pyle. For various reasons, this team has asked the authors to keep their names and exact location anonymous. As conveyed by Readey, the following outlines the depths, times, and procedures this team is using on a routine basis.

The team regularly conducts working dives in the 400-500 fsw range. They commonly dive in two working levels, plus decompression. Readey gave an example of a "typical" dive of 430 fsw for 15 minutes working, 210 fsw for eight minutes working, followed by about four hours, 40 minutes decompression. They often make two dives into the 400 fsw range in one day, always with freshly repacked scrubbers. Besides deep dives, they also make shallow dives (165 fsw and up) lasting up to nine hours. These durations are possible because they're working in warm water and working hard, eliminating thermal issues. CO_2 absorbent capacity is their limiting factor.

The team considers open circuit insufficient backup for the depths they're working, so each diver has two CCRs. They stage the backup while working. Divers also carry open-circuit scuba, used primarily for lift bags and as secondary bailout to reach the staged backup CCRs. A topside support team backs up the divers as well. After hundreds of man-hours doing this routinely for months, they have had no serious incidents. Their opinion is that given the depth, the nature of collecting fish and some of the environmental factors, there is no other UBA that would be useable for the work, irrespective of cost.

Summary

CCRs offer substantial economic and logistical advantages for deep mixed-gas diving over open-circuit systems (scuba and tethered). However, CCR deep diving requires a high degree of discipline, training and experience by the diver. Limited civilian incident data and anecdotal reports, along with the actual experiences of successful deep diving individuals and teams, suggest that 50 to 100 hours of CCR no-stop diving is a minimum experience base before beginning training for deep mixed-gas diving with the same unit. Pyle and others recommend that training emphasize following checklists closely and manual operation of a CCR. It does not appear reasonable with the present state of the art to allow lesser qualified divers to make deep CCR dives under the close supervision of high qualified divers; all divers need the appropriate experience and training. Choosing an appropriate CCR for deep diving also appears to be important.

Despite these requirements, CCRs appear to have a clear place in scientific diving. They've been used for scientific diving since at least the 1960s, and there are at least two highly successful examples of scientific divers routinely using CCRs over an extended period to work at depths below 300 fsw to as deep as 500 fsw.

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UNDERWATER HABITATS AT 300 FSW
A THING OF THE PAST, OR STILL VIABLE TODAY?

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Introduction

Establishing scientific diving capability to do significant "hands-on" in- situ marine research at 300 fsw will require a suite of deep diving techniques, each with its own merit, dependent upon the task at hand and bottom time requirement. The technique chosen should match the projected divers' bottom time requirement with the most cost effective assemblage of divers, supplies, and equipment. Following preliminary ROV surveys to identify sites of interest, initial on-site assessment by divers may require minimal mobilization costs or relatively short bottom times, thereby making techniques such as rebreathers, open-circuit mixed gas, and lightweight surface-supplied mixed gas, feasible due to their reduced costs, when compared to bell bounce or full saturation techniques.

Additional bottom time requirements for other labor intensive tasks such as core drilling to sample the geological history of a deep reef, will require larger teams of trained divers, or the use of saturation diving to maximize bottom time and vessel lease. Small sat systems, such as the commercial roll-over bell/sat systems, or even the US Navy's fly-away sat system, could be placed on research vessels of opportunity, to provide a surface platform for bell diving saturation operations. A vessel capable of dynamic positioning would allow precise station maintenance, as well as providing mobility to visit multiple sites, due primarily to the lack of need for multiple anchor mooring set-ups. These types of saturation operations have been conducted on a regular basis in commercial diving since the early '70s.

Methods

Bell saturation diving affords the marine researcher the lengthy bottom times required for some observations, experiments, and installations, but one other form of saturation diving provides the researcher with more than mere "visitor" status to the bottom site. Saturation diving from a subsea habitat or underwater laboratory, offers the researcher "residency", and he/she will observe sights unequalled even when one makes eight hour bell runs to the site. Many comparisons about marine research and habitat dwelling have been written, such as one studying forests by camping out and walking among the trees, versus flying over them in an observation aircraft. My good friend and mentor Bob Barth likens his days in the *Sealab* program to staying in a Winnebago on the floor of the Grand Canyon, as opposed to riding jackasses down the winding trails each day, spending a few hours, and then making the steep trek back to the top. I suppose he could have used burros or donkeys, but he's been known to choose his words carefully to get his point across.

Undersea laboratories or habitats have been used extensively by marine researchers for some forty years now, but sadly only one scientific habitat has operated in our oceans over the past twenty years. Despite their ability to afford researchers bottom times unequalled by non-saturated divers, and unlimited dive time at storage depth, large fixed habitat programs have almost become a thing of the past. *Aquarius*, NOAA's inner space station, was built in the mid-eighties as a mobile habitat, but its size and support requirements dictated that it was better suited for long term deployments, doubling as both a manned saturation diving platform, and an autonomous ocean observatory. Funding for large habitat programs has declined over the last ten years, and the present budget atmosphere of wet diving support offer little hope that we will see the emergence of a new deep habitat program that equals the jewels of past history such as *Sealab, Conshelf, Tektite, Hydrolab, La Chalupa, Helgoland,* and *Aegir*.

Results

Aquarius, now in its ninth year of continuous operation since returning to its Florida Keys' research site where it previously operated for three years in the mid nineties, is not rated for the 300 fsw depths presently being discussed. *Aquarius'* maximum design working depth of 120 fsw would require deep excursions, thereby limiting the bottom time at the desired deeper depths. *Aquarius* has continued to develop technology through its operations that will eventually minimize surface support components, with the hopes of making future habitats modular, more mobile, and less expensive to support topside. Advances in telemetry have enabled *Aquarius* users the ability to send real-time data and video streaming to their host universities or organizations throughout the world. Video conferencing has brought fellow researchers, students, and even astronauts in the International Space Station, down into *Aquarius* to share in the experience of the "sea dwellers". Aquanaut training has gone through many changes as well, adapting to different climates of safety concerns and individual responsibility. Underwater tracking systems and wireless diver communications, both capable of being monitored via a computer miles away, will help allow habitats to function in a more semi-autonomous mode.

Many times we find that, despite attempts to "modernize" some aspects of habitat saturation diving, the way things were done in the late 60's and 70's are still the most viable methods. We owe where we are today in bell and habitat saturation diving to all the pioneers who went before us. There will be continual upgrades to electronics and other technology, but many of the basic procedures remain true today as they did forty years ago.

Discussion

Looking back to the 60's and early 70's we find that habitats were used in conjunction with shipboard or barge mounted saturation systems. Programs like the Navy's *Sealab* project used a PTC (Personnel Transfer Capsule) to transfer aquanauts under pressure to a topside DDC (Deck Decompression Chamber) for decompression. Commercial diving operations routinely supported deep hyperbaric pipeline welding by transferring diver-welders between the ambient welding habitat and topside DDC under pressure in bells. If these methods worked in the 60's and 70's, why wouldn't their methods still be viable today?

During the turret recovery of the Civil War ironclad *USS Monitor* off Cape Hatteras in 2001-2002, open circuit mixed gas divers from NOAA/NURC, Navy surface-supplied HeO_2 divers, and Navy saturation divers, all worked simultaneously on the wreck. When the weather got rough, the NOAA divers with their drift decompression were first to cease diving operations, followed by the stage-riding Navy surface-supplied HeO_2 divers, and finally the sat divers, but only when it was too hazardous to make the bell runs through the air-sea interface as the PTC leaves or returns for DDC mating. Had there been a small ambient habitat next to the wreck, diving operations with a four man team living on bottom could have continued unaffected by the weather topside. We could look back to many diving operations like the *Monitor* and see where having the divers saturated "on site" would be the most productive method. If costs are controlled, why would this not be just as viable for scientific divers as it is for military or commercial operations? A small 8' D X 20' L habitat could provide an underwater base for a crew of four, comprised of a technician/engineer and 3 scientists, and still be manageable enough for deployment from a shipboard A-frame. Construction of the habitat as an ambient structure, instead of a pressure vessel, will minimize cost and weight. Deployment methods used previously by many habitats would entail maintaining a 2-3 psi pressure differential above ambient as the habitat is being lowered to the seabed. The umbilical supplying gas, electricity, communications, and video would be fed by the same topside facilities as the DDC. Personnel transfer to the habitat and back days later to the DDC for decompression would be conducted via the PTC. If there were circumstances necessitating the support ship to move off station, the aquanauts would be recovered to the DDC for decompression via the PTC, the umbilical disconnected topside and buoyed off, the habitat left on bottom until the weather or other emergency passed.

Conclusion

A small mobile ambient habitat, used in conjunction with a shipboard saturation system, should be considered in the arsenal of diving technologies to extend bottom times for "hands-on" undersea research at 300 fsw. It is undeniable that saturation diving offers the researcher more time at depth than any other technology, a habitat can place divers there for periods up to thirty days if desired. Large habitat systems that operated in years past have become too costly to fund in today's world, but a small habitat, essentially acting to extend bell runs from eight hours to days or weeks, could operate just as its larger counterparts did in the 60's and 70's, but for a small cost over normal sat operations. The small size would allow for system mobility and the desire to visit multiple sites. Researchers could be retrieved from one site, transported to the next site while in the DDC, and returned to the habitat once it is redeployed at the new site. Habitats have always offered researchers the ability to transfer their "surface" to the storage depth they are living at, and this becomes even more important at 300 fsw, and at depths beyond.

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AAUS DEEP DIVING STANDARDS

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Background

The scientific diving community has been operating under self-controlled diver training and education programs since 1951. This tradition continues to flourish today. One of the first set of consensual diving standards was developed by the Scripps Institution of Oceanography of the University of California (Scripps) in the early 1950's. Further, in 1973, diving safety boards and committees from ten major educational institutions involved in scientific diving met and accepted the University of California Guide for Diving Safety as a minimum standard for their individual programs.

In 1977, the Occupational Safety and Health Administration (OSHA) adopted a permanent diving standard for “Commercial Diving Operations”. This OSHA standard was designed to include scientific diving. It quickly became evident that this could present major problems for research facilities with scientific diving programs. These concerns were voiced and after a long hard fight on November 26, 1982, OSHA exempted scientific diving from coverage under 29 CFR Part 1910, Subpart T, Commercial Diving Operations, provided that the diving meets the Agency's definition of scientific diving and is under the direction and control of a diving program utilizing a safety manual and a diving control board meeting certain specified criteria [47 F.R. 53357; §1910.401(a)(2)(iv)].

The American Academy Underwater Sciences (AAUS) was organized in 1977 and incorporated in the State of California in 1983. Its Standards for scientific diving have been around since the incorporation. The title of the original AAUS standards was “Standards for Scientific Diving Certification and Operation of Scientific Diving Programs”. The AAUS standards for scientific diving were developed and written by compiling the policies set forth in diving manuals of several universities as well as both private and governmental scientific diving programs. This method set the pattern for the future development of all of the AAUS Scientific Diving Standards.

In the case of deep diving standards, the task was given to a specially formed “Technical Diving Committee”. This committee would investigate which AAUS organizational members currently had existing standards for deep diving, approved by their respective Diving Control Board (DCB), in place within their scientific diving program. Once a data bank of existing standards was acquired the technical committee would review, amend and draft a set of standards that they thought would be most appropriate for the AAUS. Once a draft for the standard was developed, the technical committee would present the draft to the AAUS Board of Directors, who after review and comment, would present to the membership for review and comment. After all comments were taken into consideration a final product would be produced, voted upon and adopted into the manual.

AAUS Scientific Diving Standards Pertaining To Deep Diving

In the original "Standards for Scientific Diving Certification and Operation of Scientific Diving Programs" manual the standards that pertained to deep diving were in a separate section. This section was titled "Other Diving Technology". It included 9 different types or modes of diving. They were listed as follows:

1. Staged Decompression Diving
2. Saturation Diving
3. Hookah Diving
4. Surface Supplied Diving
5. Closed and Semi-Closed Circuit Scuba (Rebreathers)
6. Mixed Gas Diving
7. Blue Water Diving
8. Ice and Polar Diving
9. Overhead Environments

Staged Decompression Diving

The standards for staged decompression diving existed originally as Section 2.1 in the original AAUS standards manual. In 1987, it was moved in its original form to section 9.1. It was extremely brief.

2.10 STAGED DECOMPRESSION DIVING

> *No diver shall plan or conduct staged decompression dives without prior approval of the Diving Control Board.*

This standard gives full authority to the organizational member's DCB to develop and adopt their own set of staged decompression diving standards as they should see fit. Several factors would come into play when adopting these non-consensual standards. The DCB must determine what level of safety is acceptable for their program when considering training, experience and proficiency. They must also consider what level of liability is acceptable since the standards they are producing are not consensual.

In 2001, the AAUS Technical Committee took on the task of addressing the need for consensual standards pertaining to Staged Decompression Diving. In 2003 a final draft was presented by the Technical Committee to the membership and the new Staged Decompression Diving Standards were adopted. The new standards addressed Staged Decompression Diving in its entirety. Upon completion Staged Decompression Diving was given its own separate section in the manual which was titled Section 9 Staged Decompression Diving.

SECTION 9.00 STAGED DECOMPRESSION DIVING

Decompression diving shall be defined as any diving during which the diver cannot perform a direct return to the surface without performing a mandatory decompression stop to allow the release of inert gas from the diver's body.

The following procedures shall be observed when conducting dives requiring planned decompression stops.

9.10 Minimum Experience and Training Requirements

Prerequisites:

Scientific Diver qualification according to Section 5.00.

Minimum of 100 logged dives.

Demonstration of the ability to safely plan and conduct dives deeper than 100 feet.

Nitrox certification/authorization according to AAUS Section 7.00 recommended.

Training shall be appropriate for the conditions in which dive operations are to be conducted.

Minimum Training shall include the following:

A minimum of 6 hours of classroom training to ensure theoretical knowledge to include: physics and physiology of decompression; decompression planning and procedures; gas management; equipment configurations; decompression method, emergency procedures.

It is recommended that at least one training session be conducted in a pool or sheltered water setting, to cover equipment handling and familiarization, swimming and buoyancy control, to estimate gas consumption rates, and to practice emergency procedures.

At least 6 open-water training dives simulating/requiring decompression shall be conducted, emphasizing planning and execution of required decompression dives, and including practice of emergency procedures.

Progression to greater depths shall be by 4-dive increments at depth intervals as specified in Section 5.40.

No training dives requiring decompression shall be conducted until the diver has demonstrated acceptable skills under simulated conditions.

The following are the minimum skills the diver must demonstrate proficiently during dives simulating and requiring decompression:

- *Buoyancy control*
- *Proper ascent rate*
- *Proper depth control*
- *Equipment manipulation*
- *Stage/decompression bottle use as pertinent to planned diving operation*
- *Buddy skills*
- *Gas management*
- *Time management*
- *Task loading*
- *Emergency skills*

7. ***Divers shall demonstrate to the satisfaction of the DSO or the DSO's designee proficiency in planning and executing required decompression dives appropriate to the conditions in which diving operations are to be conducted.***

8. ***Upon completion of training, the diver shall be authorized to conduct required decompression dives with DSO approval.***

9.20 Minimum Equipment Requirements

Valve and regulator systems for primary (bottom) gas supplies shall be configured in a redundant manner that allows continuous breathing gas delivery in the event of failure of any one component of the regulator/valve system.

Cylinders with volume and configuration adequate for planned diving operations.

One of the second stages on the primary gas supply shall be configured with a hose of adequate length to facilitate effective emergency gas sharing in the intended environment.

Minimum dive equipment shall include:

Snorkel is optional at the DCB's discretion, as determined by the conditions and environment.

Diver location devices adequate for the planned diving operations and environment.

Compass

Redundancy in the following components is desirable or required at the discretion of the DCB or DSO:

Decompression Schedules

Dive Timing Devices

Depth gauges

Buoyancy Control Devices

Cutting devices

Lift bags and line reels

9.30 Minimum Operational Requirements

Approval of ***dive plan applications to conduct required decompression dives shall be on a case-by-case basis.***

The maximum pO_2 ***to be used for planning required decompression dives is 1.6. It is recommended that a*** pO_2 ***of less than 1.6 be used during bottom exposure.***

Divers gas supplies shall be adequate to meet planned operational requirements and foreseeable emergency situations.

Decompression dives may be planned using dive tables, dive computers, and/or PC software approved by the DSO/DCB.

Breathing gases used while performing in-water decompression shall contain the same or greater oxygen content as that used during the bottom phase of the dive.

The dive team prior to each dive shall review emergency procedures appropriate for the planned dive.

If breathing gas mixtures other than air are used for required decompression, their use shall be in accordance with those regulations set forth in the appropriate sections of this standard.

The maximum depth for required decompression using air as the bottom gas shall be 190 feet.

Use of additional nitrox and/or high-oxygen fraction decompression mixtures as travel and decompression gases to decrease decompression obligations is encouraged.

Use of alternate inert gas mixtures to limit narcosis is encouraged for depths greater than 150 feet.

If a period of more than 6 months has elapsed since the last mixed gas dive, a series of progressive workup dives to return the diver(s) to proficiency status prior to the start of project diving operations are recommended.

Mission specific workup dives are recommended.

Surface-Supplied Diving

The standards for surface-supplied diving existed originally as Section 2.4 in the original 1984 AAUS standards manual. In 1987 it was moved in its original form to section 9.4. The standards for Surface Supplied Diving consisted of a brief outline. The original standard:

9.40 SURFACE-SUPPLIED DIVING

Surface-supplied divers shall comply with all scuba diving procedures in this manual (except Sec. 2.31). Surface-supplied diving shall not be conducted at depths greater than 190 fsw (58 msw).

9.41 Divers using the surface-supplied mode shall be equipped with a diver-carried independent reserve breathing gas supply.

9.42 Each surface-supplied diver shall be hose tended by a separate dive team member while in the water.

9.43 Divers using the surface-supplied mode shall maintain voice communication with the surface tender.

9.44 The surface-supplied breathing gas supply shall be sufficient to support all surface supplied divers in the water for the duration of the planned dive, including decompression.

9.45 During surface-supplied diving operations when only one diver is in the water, there must be a standby diver in attendance at the dive location.

The AAUS standards for Surface-Supplied Diving listed above are how they currently exist in the 2005 revision. The AAUS Standards Committee is currently considering the review, revision and adoption of a more comprehensive set of standards for Surface-Supplied Diving. Until such a revision is completed and adopted by the AAUS the responsibility for such standards will fall on the OM's DCB should an OM decide to utilize Surface-Supplied Diving. The existing set of standards, listed above, would act solely as minimum standards.

Closed- and Semi-Closed Circuit Scuba (Rebreathers)

As was the case in each of the topics listed above, the original standards for closed- and semi-closed circuit scuba (Rebreathers) were incorporated in the 1984 version of the AAUS manual. They were also moved to a new section in the 1987 revision and finally rewritten and adopted in 2005. The 1984 AAUS standards:

9.50 CLOSED AND SEMI-CLOSED CIRCUIT SCUBA (REBREATHERS)

Closed and semi-closed circuit scuba (rebreathers) shall meet the following requirements:

9.51 Oxygen partial pressure in the breathing gas shall not exceed values approved by the organizational member's DCB. The generally accepted maximum value is 1.5 atmospheres ppO_2 at depths greater than 25 fsw (7.6 msw).

9.52 Chemicals used for the absorption of carbon dioxide shall be kept in a cool, dry location in a sealed container until required for use.

9.53 The designated person-in-charge shall determine that the carbon dioxide absorption canister is used in accordance with the manufacturer's instructions.

9.54 Closed and semi-closed diving equipment will not be used at a depth greater than that recommended by the manufacturer of the equipment.

In 2003, the AAUS Standards committee identified an increasing trend towards the use of rebreathers in the Scientific Diving arena. The Technical Diving Committee was charged with providing standards for the use of rebreathers within AAUS programs. In 2005, the final draft was presented to the membership, approved and adopted by the AAUS. The final version was given its own section, Section 12 in the AAUS manual and consists of 8 pages..

SECTION 12.0 REBREATHERS

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

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

Application of this standard is in addition to pertinent requirements of all other sections of the AAUS Standards for Scientific Diving, Volumes 1 and 2.

For rebreather dives that also involve staged decompression and/or mixed gas diving, all requirements for each of the relevant diving modes shall be met. Diving Control Board reserves the authority to review each application of all specialized diving modes, and include any further requirements deemed necessary beyond those listed here on a case-by-case basis.

No diver shall conduct planned operations using rebreathers without prior review and approval of the DCB.

In all cases, trainers shall be qualified for the type of instruction to be provided. Training shall be conducted by agencies or instructors approved by DSO and DCB.

12.10 Definitions and General Information

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

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

Disadvantages of rebreathers include high cost and, in some cases, a high degree of system complexity and reliance on instrumentation for gas composition control and

monitoring, which may fail. The diver is more likely to experience hazardous levels of hypoxia, hyperoxia, or hypercapnia, due to user error or equipment malfunction, conditions which may lead to underwater blackout and drowning. Inadvertent flooding of the breathing loop and wetting of the carbon dioxide absorbent may expose the diver to ingestion of an alkaline slurry ("caustic cocktail").

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

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

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

Closed-Circuit Mixed Gas Rebreathers. Closed-circuit mixed gas rebreathers (CCR) recycle all of the exhaled gas and replace metabolized oxygen via an electronically controlled valve, governed by electronic oxygen sensors. Manual oxygen addition is available as a diver override, in case of electronic system failure. A separate inert gas source (diluent), usually containing primarily air, heliox, or trimix, is used to maintain oxygen levels at safe levels when diving below 20 fsw. CCR systems operate to maintain a constant oxygen partial pressure (PPO_2) during the dive, regardless of depth.

12.20 Prerequisites

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

Training Prerequisites

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

Completion of a minimum of 50 open-water dives on SCUBA.

For SCR or CCR, a minimum 100-fsw-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.

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

Training

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

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

Classroom training shall include:

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.

In particular, causes, signs and symptoms, first aid, treatment and prevention of the following must be covered:

- *Hyperoxia (CNS and Pulmonary Oxygen Toxicity)*
- *Middle Ear Oxygen Absorption Syndrome (oxygen ear)*
- *Hyperoxia-induced myopia*
- *Hypoxia*
- *Hypercapnia*
- *Inert gas narcosis*
- *Decompression sickness*

Rebreather-specific information required for the safe and effective operation of the system to be used, including:

- *System design and operation, including:*
- *Counterlung(s)*
- *CO_2 scrubber*
- *CO_2 absorbent material types, activity characteristics, storage, handling and disposal*
- *Oxygen control system design, automatic and manual*
- *Diluent control system, automatic and manual (if any)*
- *Pre-dive set-up and testing*
- *Post-dive break-down and maintenance*
- *Oxygen exposure management*
- *Decompression management and applicable decompression tracking methods*
- *Dive operations planning*
- *Problem recognition and management, including system failures leading to hypoxia, hyperoxia, hypercapnia, flooded loop, and caustic cocktail*
- *Emergency protocols and bailout procedures.*
- *Practical Training (with model of rebreather to be used)*

A minimum number of hours of underwater time.

Type	*Pool/Confined Water*	*O/W Training*	*O/W Supervised*
Oxygen Rebreather	*1 dive, 90 min*	*4 dives, 120 min.**	*2 dives, 60 min*
Semi-Closed Circuit	*1 dive, 90-120 min*	*4 dives, 120 min.***	*4 dives, 120 min*
Closed-Circuit	*1 dive, 90-120 min*	*8 dives, 380 min.****	*4 dives, 240 min*
** Dives should not exceed 20 fsw.* *** First two dives should not exceed 60 fsw. Subsequent dives should be at progressively greater depths, with at least one dive in the 80 to 100 fsw range.*			

**** Total underwater time (pool and open water) of approximately 500 minutes. First two open water dives should not exceed 60 fsw. Subsequent dives should be at progressively greater depths, with at least 2 dives in the 100 to 130 fsw range.*

Amount of required in-water time should increase proportionally to the complexity of rebreather system used.

Training shall be in accordance with the manufacturer's recommendations.

Practical Evaluations

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

- *Oxygen control system calibration and operation checks*
- *Carbon dioxide absorbent canister packing*
- *Supply gas cylinder analysis and pressure check*
- *Test of one-way valves*
- *System assembly and breathing loop leak testing*
- *Pre-dive breathing to test system operation*
- *In-water leak checks*
- *Buoyancy control during descent, bottom operations, and ascent*
- *System monitoring and control during descent, bottom operations, and ascent*
- *Proper interpretation and operation of system instrumentation (PO2 displays, dive computers, gas supply pressure gauges, alarms, etc, as applicable)*
- *Unit removal and replacement on the surface.*
- *Bailout and emergency procedures for self and buddy, including:*
- *System malfunction recognition and solution*
- *Manual system control*
- *Flooded breathing loop recovery (if possible)*
- *Absorbent canister failure*
- *Alternate bailout options*
- *Symptom recognition and emergency procedures for hyperoxia, hypoxia, and hypercapnia*
- *Proper system maintenance, including:*
- *Full breathing loop disassembly and cleaning (mouthpiece, check-valves, hoses, counterlung, absorbent canister, etc.)*
- *Oxygen sensor replacement (for SCR and CCR)*
- *Other tasks required by specific rebreather models*

Written Evaluation

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

Supervised Rebreather Dives

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

Supervisor for these dives should be the DSO or designee, and should be an active scientific diver experienced in diving with the make/model of rebreather being used.

Dives at this level may be targeted to activities associated with the planned science diving application. See the following table for number and cumulative water time for different rebreather types.

Type	*Pool/Confined Water*	*O/W Training*	*O/W Supervised*

Oxygen Rebreather	*1 dive, 90 min*	*4 dives, 120 min.**	*2 dives, 60 min*
Semi-Closed Circuit	*1 dive, 90-120 min*	*4 dives, 120 min.***	*4 dives, 120 min*
Closed-Circuit	*1 dive, 90-120 min*	*8 dives, 380 min.****	*4 dives, 240 min*

** Dives should not exceed 20 fsw.*

*** First two dives should not exceed 60 fsw. Subsequent dives should be at progressively greater depths, with at least one dive in the 80 to 100 fsw range.*

**** Total underwater time (pool and open water) of approximately 500 minutes. First two open water dives should not exceed 60 fsw. Subsequent dives should be at progressively greater depths, with at least 2 dives in the 100 to 130 fsw range.*

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

Extended Range, Required Decompression and Helium-Based Inert Gas

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

As a prerequisite for training in staged decompression using rebreathers, the diver shall have logged a minimum of 25 hours of underwater time on the rebreather system to be used, with at least 10 rebreather dives in the 100 fsw to 130 fsw range.

As a prerequisite for training for use of rebreathers with gas mixtures containing inert gas other than nitrogen, the diver shall have logged a minimum of 50 hours of underwater time on the rebreather system to be used and shall have completed training in stage decompression methods using rebreathers. The diver shall have completed at least 12 dives requiring staged decompression on the rebreather model to be used, with at least 4 dives near 130 fsw.

Training shall be in accordance with standards for required-decompression and mixed gas diving, as applicable to rebreather systems, starting at the 130 fsw level.

Maintenance of Proficiency

To maintain authorization to dive with rebreathers, an authorized diver shall make at least one dive using a rebreather every 8 weeks. For divers authorized for the conduct of extended range, stage decompression or mixed-gas diving, at least one dive per month should be made to a depth near 130 fsw, practicing decompression protocols.

For a diver in arrears, the DCB shall approve a program of remedial knowledge and skill tune-up training and a course of dives required to return the diver to full authorization. The extent of this program should be directly related to the complexity of the planned rebreather diving operations.

12.30 Equipment Requirements

General Requirements

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

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.

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

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.

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 PPO_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.

A maintenance log is required. The unit maintenance shall be up-to-date based upon manufacturer's recommendations.

Minimum Equipment

A surface/dive valve in the mouthpiece assembly, allowing sealing of the breathing loop from the external environment when not in use.

An automatic gas addition valve, so that manual volumetric compensation during descent is unnecessary.

Manual gas addition valves, so that manual volumetric compensation during descent and manual oxygen addition at all times during the dive are possible.

The diver shall carry alternate life support capability (open-circuit bail-out or redundant rebreather) sufficient to allow the solution of minor problems and allow reliable access to a pre-planned alternate life support system.

Oxygen Rebreathers

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

Semi-Closed Circuit Rebreathers.

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

Closed-Circuit Mixed-gas Rebreathers.

CCR shall incorporate a minimum of three independent oxygen sensors.

A minimum of two independent displays of oxygen sensor readings shall be available to the diver.

Two independent power supplies in the rebreather design are desirable. If only one is present, a secondary system to monitor oxygen levels without power from the primary battery must be

incorporated.

CCR shall be equipped with manual diluent and oxygen addition valves, to enable the diver to maintain safe oxygen levels in the event of failure of the primary power supply or automatic gas addition systems.

Redundancies in onboard electronics, power supplies, and life support systems are highly desirable.

12.40 Operational Requirements

General Requirements

All dives involving rebreathers must comply with applicable operational requirements for open-circuit SCUBA dives to equivalent depths.

No rebreather system should be used in situations beyond the manufacturer's stated design limits (dive depth, duration, water temperature, etc).

Modifications to rebreather systems shall be in compliance with manufacturer's recommendations.

Rebreather maintenance is to be in compliance with manufacturer's recommendations including sanitizing, replacement of consumables (sensors, CO_2 absorbent, gas, batteries, etc) and periodic maintenance.

Dive Plan. In addition to standard dive plan components stipulated in AAUS Section 2.0, all dive plans that include the use of rebreathers must include, at minimum, the following details:

- *Information about the specific rebreather model to be used*
- *Make, model, and type of rebreather system*
- *Type of CO_2 absorbent material*
- *Composition and volume(s) of supply gases*
- *Complete description of alternate bailout procedures to be employed, including manual rebreather operation and open-circuit procedures*
- *Other specific details as requested by DCB*

Buddy Qualifications.

A diver whose buddy is diving with a rebreather shall be trained in basic rebreather operation, hazard identification, and assist/rescue procedures for a rebreather diver.

If the buddy of a rebreather diver is using open-circuit scuba, the rebreather diver must be equipped with a means to provide the open-circuit scuba diver with a sufficient supply of open-circuit breathing gas to allow both divers to return safely to the surface.

Oxygen Exposures

Planned oxygen partial pressure in the breathing gas shall not exceed 1.4 atmospheres at depths greater than 30 feet.

Planned oxygen partial pressure set point for CCR shall not exceed 1.4 atm. Set point at depth should be reduced to manage oxygen toxicity according to the NOAA Oxygen Exposure Limits.

Oxygen exposures should not exceed the NOAA oxygen single and daily exposure limits. Both CNS and pulmonary (whole-body) oxygen exposure indices should be tracked for each diver.

Decompression Management

DCB shall review and approve the method of decompression management selected for a given diving application and project.

Decompression management can be safely achieved by a variety of methods, depending on the type and model of rebreather to be used. Following is a general list of methods for different rebreather types:

Oxygen rebreathers: Not applicable.

SCR (presumed constant FO_2):

- *Use of any method approved for open-circuit scuba diving breathing air, above the maximum operational depth of the supply gas.*
- *Use of open-circuit nitrox dive tables based upon expected inspired FO_2. In this case, contingency air dive tables may be necessary for active-addition SCRs in the event that exertion level is higher than expected.*
- *Equivalent air depth correction to open-circuit air dive tables, based upon expected inspired FO_2 for planned exertion level, gas supply rate, and gas composition. In this case, contingency air dive tables may be necessary for active-addition SCRs in the event that exertion level is higher than expected.*

CCR (constant PPO_2):

- *Integrated constant PPO_2 dive computer.*
- *Non-integrated constant PPO_2 dive computer.*
- *Constant PPO_2 dive tables.*
- *Open-circuit (constant FO_2) nitrox dive computer, set to inspired FO_2 predicted using PPO_2 set point at the maximum planned dive depth.*
- *Equivalent air depth (EAD) correction to standard open-circuit air dive tables, based on the inspired FO_2 predicted using the PPO_2 set point at the maximum planned dive depth.*
- *Air dive computer, or air dive tables used above the maximum operating depth (MOD) of air for the PPO_2 setpoint selected.*

Maintenance Logs, CO_2 Scrubber Logs, Battery Logs, and Pre-And Post-Dive Checklists

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

- *Gas supply cylinders full*
- *Composition of all supply and bail-out gases analyzed and documented*
- *Oxygen sensors calibrated*
- *Carbon dioxide canister properly packed*
- *Remaining duration of canister life verified*
- *Breathing loop assembled*
- *Positive and negative pressure leak checks*
- *Automatic volume addition system working*
- *Automatic oxygen addition systems working*
- *Pre-breathe system for 3 minutes (5 minutes in cold water) to ensure proper oxygen addition and carbon dioxide removal (be alert for signs of hypoxia or hypercapnia)*
- *Other procedures specific to the model of rebreather used*
- *Documentation of ALL components assembled*
- *Complete pre-dive system check performed*
- *Final operational verification immediately before to entering the water:*
- *PO_2 in the rebreather is not hypoxic*
- *Oxygen addition system is functioning;*
- *Volumetric addition is functioning*
- *Bail-out life support is functioning*

Alternate Life Support System

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

Open-circuit bailout cylinders or sets of cylinders, either carried or pre-positioned

Redundant rebreather

Pre-positioned life support equipment with topside support

CO_2 Absorbent Material

CO_2 absorption canister shall be filled in accordance with the manufacturer's specifications.

CO_2 absorbent material shall be used in accordance with the manufacturer's specifications for expected duration.

If CO_2 absorbent canister is not exhausted and storage between dives is planned, the canister should be removed from the unit and stored sealed and protected from ambient air, to ensure the absorbent retains its activity for subsequent dives.

Long-term storage of carbon dioxide absorbents shall be in a cool, dry location in a sealed container. Field storage must be adequate to maintain viability of material until use.

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

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

Unit Disinfections

The entire breathing loop, including mouthpiece, hoses, counterlungs, and CO2 canister, should be disinfected periodically according to manufacturer's specifications. The loop must be disinfected between each use of the same rebreather by different divers.

12.50 Oxygen Rebreathers

Oxygen rebreathers shall not be used at depths greater than 20 feet.

Breathing loop and diver's lungs must be adequately flushed with pure oxygen prior to entering the water on each dive. Once done, the diver must breathe continuously and solely from the intact loop, or re-flushing is required.

Breathing loop shall be flushed with fresh oxygen prior to ascending to avoid hypoxia due to inert gas in the loop.

12.60 Semi-Closed Circuit Rebreathers

The composition of the injection gas supply of a semi-closed rebreather shall be chosen such that the partial pressure of oxygen in the breathing loop will not drop below 0.2 atm, even at maximum exertion at the surface.

The gas addition rate of active addition SCR (e.g., Draeger Dolphin and similar units) shall be checked before every dive, to ensure it is balanced against expected workload and supply gas FO_2.

The intermediate pressure of supply gas delivery in active-addition SCR shall be checked periodically, in compliance with manufacturer's recommendations.

Maximum operating depth shall be based upon the FO_2 in the active supply cylinder.

Prior to ascent to the surface the diver shall flush the breathing loop with fresh gas or switch to an open-circuit system to avoid hypoxia. The flush should be at a depth of approximately 30 fsw during ascent on dives deeper than 30 fsw, and at bottom depth on dives 30 fsw and shallower.

12.70 Closed-Circuit Rebreathers

The FO_2 of each diluent gas supply used shall be chosen so that, if breathed directly while in the depth range for which its use is intended, it will produce an inspired PPO_2 greater than 0.20 atm but no greater than 1.4 atm.

Maximum operating depth shall be based on the FO_2 of the diluent in use during each phase of the dive, so as not to exceed a PO_2 limit of 1.4 atm.

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).

The PPO_2 set point shall not be lower than 0.4 atm or higher than 1.4 atm.

Mixed Gas Diving

The standards for Mixed Gas Diving existed originally as Section 2.6 in the AAUS standards manual. In 1987 it was moved intact to section 9.6. It existed as nothing more than a title.

9.60 MIXED GAS DIVING

If an AAUS OM were to conduct any Mixed Gas Diving their DCB would have to produce Mixed Gas Diving standards in their entirety. Similar to the way the Technical Diving Committee took on the task of adopting standards for rebreather diving they the task to develop standards for mixed gas diving. In 2003 the AAUS adopted the Mixed Gas Diving standards. They designated Section 10 of the AAUS Standards manual to Mixed Gas Diving. Following are the standards for Mixed Gas Diving as they appear in the 2005 version of the AAUS Standards:

section 10.00 MIXED GAS DIVING

Mixed gas diving is defined as dives done while breathing gas mixes containing proportions greater than 1% by volume of an inert gas other than nitrogen.

10.10 Minimum Experience and Training Requirements

Prerequisites:

Nitrox certification and authorization (Section 7.00)

If the intended use entails required decompression stops, divers will be previously certified and authorized in decompression diving (Section 9.00).

Divers shall demonstrate to the DCB's satisfaction skills, knowledge, and attitude appropriate for training in the safe use of mixed gases.

Classroom training including:

Review of topics and issues previously outlined in nitrox and required decompression diving training as pertinent to the planned operations.

The use of helium or other inert gases, and the use of multiple decompression gases.

Equipment configurations

Mixed gas decompression planning

Gas management planning

Thermal considerations

END determination

Mission planning and logistics

Emergency procedures

Mixed gas production methods

Methods of gas handling and cylinder filling

Oxygen exposure management

Gas analysis

Mixed gas physics and physiology

Practical Training:

Confined water session(s) in which divers demonstrate proficiency in required skills and techniques for proposed diving operations.

A minimum of 6 open water training dives.

At least one initial dive shall be in 130 feet or less to practice equipment handling and emergency procedures.

Subsequent dives will gradually increase in depth, with a majority of the training dives being conducted between 130 feet and the planned operational depth.

Planned operational depth for initial training dives shall not exceed 260 feet.

Diving operations beyond 260 feet requires additional training dives.

10.20 Equipment and Gas Quality Requirements

Equipment requirements shall be developed and approved by the DCB, and met by divers, prior to engaging in mixed-gas diving. Equipment shall meet other pertinent requirements set forth elsewhere in this standard.

The quality of inert gases used to produce breathing mixtures shall be of an acceptable grade for human consumption.

10.30 Minimum Operational Requirements

Approval of dive plan applications to conduct mixed gas dives shall be on a case-by-case basis.

All applicable operational requirements for nitrox and decompression diving shall be met.

The maximum pO_2 ***to be used for planning required decompression dives is 1.6. It is recommended that a*** pO_2 ***of less than 1.6 be used during bottom exposure.***

Maximum planned Oxygen Toxicity Units (OTU) will be considered based on mission duration.

Divers decompressing on high-oxygen concentration mixtures shall closely monitor one another for signs of acute oxygen toxicity.

If a period of more than 6 months has elapsed since the last mixed gas dive, a series of progressive workup dives to return the diver(s) to proficiency status prior to the start of project diving operations are recommended.

Potential ramifications that come into play with the acceptance of consensual standards

When standards are purposely left vague such as the original Mixed Gas Diving standards the onus to produce safe workable standards is put on the individual DCB. The DCB must develop specific standards that best fit their own scientific diving program while at the same time it must realize it opens the door for additional problems. One such problem is the concept of reciprocity between OMs. If an OM has adopted standards specific to a type of diving their program utilizes then if they were to try to utilize reciprocity with another AAUS OM the accepting OM would have to have their DCB review and accept that specific set of standards. This could become a very long laborious process.

AAUS Statistics – Is Underwater Research Moving Towards Deeper Water?

In order to understand the AAUS statistical process you must first take a look at who is submitting the data. Each AAUS organizational member (OM) must submit their organization's diving data on an annual basis. In 1998, the AAUS revised its process for collecting dive data. The following tables utilize 1998 as a starting point.

When I first started looking at the AAUS statistics I thought that the diver per OM while on surface-supplied data would prove valuable. It quickly became evident that

AAUS had an issue on what was being reported as surface-supplied diving. After a few telephone calls it was quickly determined that some organizational members were confusing surface-supplied diving with hookah diving. As you can see in the first portion of this paper, the AAUS standards for surface-supplied diving are very limited. When the surface-supplied diving standards are readdressed a definition needs to head the section. The same applies to the AAUS standards for hookah diving. Ironically, with a bit more searching I found that the AAUS Statistical Committee had a definition in place for the purpose of reporting statistics. The problem may lie in the fact that some of the organizational members may have been incorrectly labeling their dives since the beginning of reporting, prior to the stats definition. It will be proposed that, at the very least, the AAUS Standards Committee consider the following definition for surface-supplied diving for immediate incorporation:

Dives where the breathing gas is supplied from the surface by means of a pressurized umbilical hose. The umbilical generally consists of a gas supply hose, strength member, pneumofathometer hose, and communication line. The umbilical supplies a helmet or full-face mask. The diver may rely on the tender at the surface to keep up with the divers' depth, time and diving profile.

It will also be proposed that, at the minimum, the AAUS Standards Committee consider the following definition for hookah diving for immediate incorporation:

While similar to surface-supplied diving in that the breathing gas is supplied from the surface by means of a pressurized hose, the supply hose does not require a strength member, pneumofathometer hose, or communication line. Hookah equipment may be as simple as a long hose attached to a standard scuba cylinder supplying a standard scuba second stage. The diver is responsible for the monitoring his/her own depth, time, and diving profile

Due to the fact that there is no way to differentiate between the data supplied for hookah diving from the data supplied for surface-supplied diving it becomes pointless to make any conclusions using either data.

AAUS Statistical Data

Total # of OM reporting, # of Divers, # of Dives and # of Minutes

	1998	1999	2000	2001	2002	2003	2004
OM Reporting	64	52	47	65	69	79	87
# of Divers	3749	2802	4176	4044	3218	3719	3872
# of Dives	68,970	66,271	63,956	85,273	101,046	107,414	119464
# of Minutes	3,060,689	2,947,656	2,831,959	3,319,630	4,079,629	4,345,642	4,947,650

The data submitted by the AAUS organizational membership must be categorized utilizing several criteria. The next table illustrates how the total numbers, listed in the table above, is broken down when viewing by type of dives.

AAUS OM Dives By Mode

	1998	1999	2000	2001	2002	2003	2004
Open Circuit	51 OM 64,277	51 OM 59,521	47 OM 57,121	63 OM 79,704	66 OM 97,191	76 OM 102,046	84 OM 110,518

	dives	dives	dives	dives	dives	dives	dives
Hookah	9 OM 223 dives	14 OM 5,680 dives	12 OM 993 dives	10 OM 2,452 dives	12 OM 3,064 dives	19 OM 6,615 dives	19 OM 5,528 dives
Surface Supplied	7 OM 141 dives	9 OM 969 dives	7 OM 3135 dives	13 OM 1,395 dives	9 OM 1131 dives	9 OM 3,033 dives	9 OM 2598 dives
Rebreather	9 OM 22 dives	5 OM 53 dives	5 OM 100 dives	11 OM 322 dives	8 OM 308 dives	9 OM 445 dives	13 OM 289 dives

Each AAUS Organizational Member must submit statistics which would indicate any diving which would require decompression as well as dives utilizing mixed gases.

AAUS OM Dives on Mixed Gas and Required Decompression

	1998	1999	2000	2001	2002	2003	2004
Mixed Gas	5 OM 31 dives	5 OM 57 dives	5 OM 112 dives	7 OM 241 dives	13 OM 236 dives	12 OM 183 dives	14 OM 214 dives
Required Decompression	8 OM 310 dives	10 OM 175 dives	10 OM 275 dives	13 OM 370 dives	16 OM 377 dives	20 OM 493 dives	22 OM 545 dives

The AAUS utilizes a series of stepped depth ranges when recording diving statistics. This has been in place since the AAUS started collecting scientific diving data. Each step towards a deeper diving certification has specific requirements that must be met before a deeper range is granted to the diver. The depth ranges are as follows:

- 0 fsw – 30 fsw
- 31 fsw – 60 fsw
- 61 fsw – 100 fsw
- 101 fsw – 130 fsw
- 131 fsw – 150 fsw
- 151 fsw – 190 fsw
- 191 fsw and deeper

Although the AAUS records all dives regardless of depth, the tables below will only list those dives completed in the depth range of 101 fsw and deeper.

Dives by AAUS OM per Depth Range per Year

	1998	1999	2000	2001	2002	2003	2004
101 – 130 fsw	37 OM 1277 dives	40 OM 990 dives	39 OM 1217 dives	50 OM 1264 dives	48 OM 1522 dives	49 OM 1556 dives	58 OM 2052 dives
131 – 150 fsw	17 OM 158 dives	19 OM 101 dives	23 OM 359 dives	24 OM 374 dives	25 OM 377 dives	28 OM 489 dives	32 OM 449 dives
151 – 190 fsw	9 OM 79 dives	11 OM 57 dives	10 OM 100 dives	14 OM 158 dives	20 OM 131 dives	22 OM 157 dives	18 OM 162 dives
191 and deeper	6 OM 25 dives	8 OM 31 dives	2 OM 66 dives	8 OM 149 dives	13 OM 200 dives	13 OM 161 dives	9 OM 84 dives

AAUS Organizational Members reporting dives deeper than 151 fsw in the last five years:

1. Bermuda Biological Station for Research
2. California Department of Fish and Game
3. East Carolina University
4. Florida Fish and Wildlife Research Institute
5. Harbor Branch Oceanographic Institution
6. International Innerspace Institute, Inc.
7. Louisiana Universities Marine Consortium
8. Marine Biological Laboratory
9. MBC Applied Environmental Sciences
10. Mote Marine Laboratory
11. Northeastern University
12. Perry Institute For Marine Science (CMRC)
13. Scripps Institution of Oceanography
14. Smithsonian Institution
15. Texas A & M University – Galveston
16. The Florida Aquarium
17. The Oceanic Institute
18. University of New Hampshire
19. Underwater Archaeology Branch
20. University of California – Santa Barbara
21. University of California – Santa Cruz
22. University of Connecticut – MSTC
23. University of Florida
24. University of Hawaii
25. University of Miami – RSMAS
26. University of North Carolina at Wilmington
27. University of South Florida
28. University of Southern California
29. Virginia Institute of Marine Science

AAUS Organizational Members utilizing Mixed Gas or Rebreathers:

1. Aquarium of the Pacific
2. California Department of Fish and Game
3. California State University
4. Florida Fish and Wildlife Research Institute
5. International Innerspace Institute, Inc.
6. J F White Contracting Company
7. NIWA – New Zealand
8. Scripps Institution of Oceanography
9. Shannon Point Marine Center
10. Texas A & M University – Galveston
11. University of Alaska
12. University of California – Davis
13. University of California – Santa Cruz
14. University of Connecticut – MSTC
15. University Of Hawaii
16. University of North Carolina at Wilmington
17. University of Southern California
18. University of South Florida

Do the AAUS statistical data show a trend towards deeper diving?

Each year the AAUS has continued to increase its membership. In 1998, the AAUS had 64 organizational members report their statistics. The number of AAUS organizational members reporting in 2004 had increased to 87 – a 36% increase. The easiest way to measure whether there is a trend towards deeper diving is to compare the ratio of the number of dives completed divided by the number of OMs completing those dives. Then we can compare this ratio from the earliest years to the most current year.

Dives utilizing Rebreathers (% increase in the number of dives/OM)

	1998 dives/OM	2004 dives/OM	% increase dives/OM
Rebreather Dives/OM	2.4	22.2	+825 %

Depth Ranges (% increase in the number of dives/OM)

Depth Range	1998 dives/OM	2004 dives/OM	% increase dives/OM
101 – 130 fsw	34.5	35.4	+2.6 %
131 – 150 fsw	9.3	14.0	+50.5 %
151 – 190 fsw	8.8	9.0	+2.3 %
191 fsw and deeper	4.2	9.3	+121.4%

Decompression and/or Mixed Gases (% increase in the number of dives/OM)

	1998 dives/OM	2004 dives/OM	% increase dives/OM
Mixed Gas Dives/OM	6.2	15.3	+146.8 %
Deco Dives Dives/OM	38.8	24.0	- 38.1 %

Trends

Mixed-gas diving

AAUS statistical data suggests a strong trend in the increased use (+ 146%) of mixed-gas diving over the past 7 years.

Deep diving technology – Rebreathers

Depending on the design, rebreathers are not necessarily depth restricted and can be ideally suited for the deepest depths. They are included in this comparison but it is impossible, due to current AAUS data collection methods, to extract the depth ranges for rebreather dives. AAUS statistical data does suggests a strong trend in the increased use (increase of 825%) of the rebreather in the past 7 years.

Surface-supplied diving

AAUS statistical data is of no use when analyzing this mode of diving for “deep” dives as defined by this workshop.

Dives at deeper depths

There seems to be a clear trend towards increased research activity in deeper depths, particularly over 190 fsw, showing an increase of 121% in the past 7 years.

The final trend

The AAUS had recognized the trend towards deeper water research early on. In the past 5 years, the AAUS has concentrated the resources of its Standards Committee towards deep diving standards. In the past few years, the AAUS Technical Committee has completed standards for stage decompression, mixed-gas diving and rebreathers. Standards for blue-water diving are progressing and the AAUS Standards Committee will probably address surface-supplied diving standards in the near future.

NOAA'S SURFACE-SUPPLIED DIVING PROGRAM: PAST, PRESENT AND FUTURE

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Introduction

The National Oceanographic and Atmospheric Administration (NOAA) administers a variety of programs that require research below the surface of the water. Methodologies include the use of diving, ROVs, and submersibles. Both the NOAA Diving Program and the NOAA Undersea Research Program utilize wet diving.

Intramural Diving Program

The NOAA Diving Program (NDP) trains, certifies, and equips NOAA employees and contractors to perform a variety of underwater tasks in support of NOAA's mission and to ensure that all diving operations are conducted safely, efficiently, and economically. NOAA has 500+ active divers in 57 locations throughout the United States, including Alaska, Hawaii, and American Samoa, and on all 19 NOAA ships. The headquarters for the dive program is located at the NOAA Western Regional Center in Seattle, Washington.

NDP's experience with surface-supplied diving is limited. In the 1980s, the dive program developed and tested hybrid surface-supplied diving systems and specialized equipment for diving in polluted water. Operationally, there were less than 10 surface-supplied diving missions between 1970-date. The last mission was to the U.S.S. MONITOR in 1993. At present, the NDP only conducts surface-supplied familiarization dives once a year in the dive center's training tower during the Diving Medical Officer class. Future plans include the development of shallow-water tethered scuba and lightweight surface-supplied diving programs.

Extramural Diving Program

The NOAA Undersea Research Program (NURP) provides scientists with the tools and expertise they need to investigate the undersea environment, including submersibles, remotely operated vehicles, autonomous underwater vehicles, mixed-gas diving equipment, underwater laboratories and observatories, and other cutting edge technologies. NURP is comprised of six regional Centers and a National Institute and is headquartered at the NOAA complex in Silver Spring, Maryland.

NURP's experience with surface-supplied diving has been confined primarily to two Centers: the University of North Carolina at Wilmington, North Carolina and Rutgers University in New Jersey.

From 1982 thru 1985, NURC/UNCW operated the R/V SEAHAWK and conducted undersea research in the South Atlantic Bight using commercial diving equipment and techniques (*i.e.,* surface-supplied diving). In 1986, the program was discontinued due to inadequacies of the support vessel, and limitations of the technology and number of interested/qualified scientists. In December 1986, the Center sold the R/V SEAHAWK and adopted a multidisciplinary approach to operations using nitrox scuba, ROVs, and leased manned submersibles. Currently, NURC/UNCW uses surface-supplied diving for deploying and retrieving the Aquarius undersea laboratory, as well as performing shallow, close range excursions from the habitat.

NURC/Rutgers currently uses surface-supplied diving for science-related work on the underwater observatory, LEO-15. The Center has no plans to expand the use surface-supplied diving in the future.

NURC/UNCW Diving Program

The Center at UNCW was established by NOAA in 1980 through a national competitive process. Originally called the Southeast Undersea Research Facility (SURF), the title was later changed to NURC. The program utilized a mobile diving platform (R/V SEAHAWK) and commercial diving equipment and techniques to place scientists on the seafloor.

The R/V SEAHAWK was a converted 80-foot shrimp trawler with a 3-point mooring system. Equipped with berthing for 14 for up to 10 days duration on station, it was capable of 7-9 knots speed and operated from Cape May, NJ to the Flower Gardens in the Gulf of Mexico. Personnel included a Captain, Engineer, Cook and additional crew provided by the diving staff. The onboard diving systems included KMB masks and Superlite 17 helmets, a 60-inch double-lock recompression chamber, two HP air compressors, air, nitrox and HeO_2 gas storage cylinders, a three-diver console, and a Class II diving bell. The diving staff included one diving supervisor and four divers/tenders.

Surface-supplied dive training

Surface-supplied dive training prerequisites consisted of proof of scuba certification, a diving physical examination, and 25 logged dives. The four-day training program, which was taught immediately prior to the start of a mission, included classroom theory and pool and confined water exercises.

The classroom training curriculum covered surface-supplied diving equipment, diving and tending procedures, dressing/undressing procedures, in-water and surface decompression tables and procedures, and emergency procedures such as loss of umbilical supply. The practical sessions involved tending procedures, dressing/undressing the diver, entering/exiting the water, voice and line-pull communications, tether management, and simulated emergency situations such a loss of primary gas supply or voice communications.

NURC/UNCW surface-supplied diving standards

The minimal staffing level required a diving supervisor, rack operator, standby diver, and two tenders. Minimum equipment included masks or helmets, voice communications, umbilicals, gas supplies, gas rack/console, diver worn equipment (*e.g.,* bail-out bottle, weight belt, safety harness, boots/fins, and knife), a recompression chamber, and a diver stage or bell with deployment capability.

Depth limits were restricted to 190 fsw on air and 300 fsw on mixed gas, with bottom times limited to those in the U.S. Navy air and HeO_2 decompression tables. Environmental conditions for surface-supplied diving could not exceed 3-5 foot seas, current over 1 knot, and wind over 20 knots.

Table 1. NURC/UNCW Surface-Supplied Diving Statistics.

Depths (fsw)	0-25	26-50	51-75	76-100	101-125	126-150	151-175	176-200
Dives	15	7	5	27	44	74	13	2

	1983	1984	1985
Dives per year	45	76	66
Hours BT	15	41	26

Lessons Learned

The diving platform must have adequate open deck space and be stable and capable of holding station in changing sea conditions, winds, and currents.

Surface-supplied diving requires substantial pre-dive preparations and offers limited vertical and horizontal mobility compared to scuba. Diver thermal protection must be considered due to longer bottom times and voice communications are definitely a positive feature. Such diving is not for everyone. Some scientific divers do not have the physical strength to handle the gear, and others may never get comfortable with it. Four days is not enough time to train the average scuba diver to become comfortable and competent in surface-supplied diving equipment for moderate to deep open-sea diving. Additionally, once trained most scientists cannot maintain surface-supplied diving proficiency at their home institutions. Surface-supplied diving requires an appropriate number of trained and experienced professional divers to serve in support roles. And finally, diving support personnel (*i.e.,* divers, tenders, supervisors) should not be used in other capacities aboard (*e.g.,* standing watches) that prevent them from getting adequate rest.

Conclusions

Surface-supplied diving operations can be a viable diving mode for certain research applications. The limiting factors are the availability of stable platforms, adequate training and experience of scientists, and professional support staff. Scientists must be comfortable in the gear in order to be productive. In NOAA's experience, moderate to deep open-sea dives using surface-supplied equipment from a stage or open-bottom bell may have limited application for the average scientific diver.

THE TRANSITION FROM SCUBA TO WAYSTATION SURFACE-SUPPLIED DIVING

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Introduction

From 1984-1985, the NOAA/USC Interim Science Program was established at the USC Catalina Marine Science Center in anticipation of the deployment at Catalina Island of the saturation habitat now known as Aquarius. A Waystation and Tether Training Program was developed by NURP Science Program Director Bob Given, Hyperbaric Chamber Director Andy Pilmanis, and Operations Director Jack Baldelli. Two 4-day missions (130 fsw max. depth) were performed by Peter Haaker (California Department of Fish and Game) and Michael Lang (San Diego State University) investigating white abalone and California octopus. The training program's duration was two days long, more than adequate to acquire the necessary skills for the operational aspects of this waystation surface-supplied diving system.

Training Curriculum

1. Introduction
2. System and Equipment
    a. Air supply (sources, regulator, mask and helmets, umbilical)
    b. Communications
    c. Pneumofathometer
    d. Buoyancy control
    e. Thermal protection
    f. Weight system
    g. Knife
3. Regulations
    a. Qualifications
    b. Rules
4. Operations
    a. Dive team responsibilities (diver, tender, stand-by diver, shoreside support)
    b. Pre-dive preparations (mask, helmet, dressing)
    c. The dive (communications, dive plan)
    d. Post-dive

    e. Emergency procedures (loss of verbal communication, air supply failure, fouling, blow-up
5. Training
    a. Instruction outline
    b. Training schedule
6. Exposure dives
    a. Requirements
    b. The dive
7. Appendices: requirements for primary and secondary breathing gases, bail-out, umbilical hose, line pull signals

The Waystation System

The waystation system (Fig. 1a and b) is a mobile unit consisting of an anchor plate, an open bell with skirt, and a surface support barge (Fig. 2a and b), positioned above it. Umibilicals are stored on the outisde of the bell, as are oxygen cylinders used for decompression.

Figure 1. Waystation system.

Topside Support

Hot water and compressed air were supplied from a surface-support barge directly above the waystation, anchored to the bottom (110 fsw) with a 1,000 lb weight. Support boats ferried staff and supplies from shore and stood by in case of diver emergencies. This particular program was supported through the immediate proximity of the Catalina Hyperbaric Chamber.

Figure 2. Support barge with hot water and air supply.

The Crew Chief

The success of this program and its participants is attributed to a large degree to the commercial diving experience and qualifications of the all-important crew chief (Fig. 3). It remains an example of operational efficiency and scientific productivity through the application of commercial diving technology to the scientific community. The control of the dive was performed topside. The diver to surface communications system allowed the scientific diver to focus on the research task and leave all operational aspects to the crew chief such as gas supply, bottom time and depth recordings, decompression stops, oxygen breathing, equipment performance, and hot water supply.

Figure 3. Jack Baldelli (Crew Chief) controlled the dive: hot water supply, breathing gases, communications, and decompression.

The Transition from Scuba to Surface-Supplied Diving

Perhaps the most revealing aspect of the transition from scuba to surface-supplied diving was the ease by which it was accomplished, under this training program and in this particular environment. With an experienced crew chief topside and using first-rate surface-supplied equipment, those of us whose experience base was mainly in open-circuit, compressed air scuba in temperate California kelp beds experienced several advantages. Heretofore having to rely on dry suits or ¾" wetsuits we now had the luxury of a simple 3 mm wetsuit with hot water supplied through a hose ending in a "T" on the chest, inserted through the wetsuit collar. So effective was this system that no gloves were needed as the hot water flooded through the suit and created a visible warm water envelope flowing out through the sleeves around the hands.

The need for a heavy weight belt was obviated, providing a lightweight sense of freedom of movement. The use of a horse-collar front buoyancy compensator (bc) was mandated and this created for some of us a source of distraction for several reasons: the front side of the diver was encumbered, and the buoyancy mechanics of a front bc have a tendency to try to invert the diver while in a horizontal swimming position, our orientation for the majority of the dive. A back-mount bc or wings that provide buoyancy more similar to that of a hot air balloon concept with the negative ballast, diver and gear, positioned below the positive buoyancy component is preferable. A bail-out system with cylinder was harnessed to the diver's back.

The management of the umbilical, in this particular environment devoid of overhead obstructions and currents in Big Fisherman's Cove, was a non-issue. It is expected that a similar experience would be had descending along a coral reef wall on a multi-level dive for deep science projects. The exploration of the bottom habitat for the two cryptic target species, white abalone (Haliotis sorenseni) and California two-spot octopus (Octopus bimaculatus), did not require extensive horizontal excursions.

Conclusion

For this project in this specific environment, the waystation surface-supplied diving method worked flawlessly. The 2-day training session for experienced scientific divers was sufficient to allow for an immediate focus on the scientific objectives. Safety and support were outstanding and the importance of an experienced crew chief cannot be overemphasized. This type of system allows for significant flexibility and can be readily moved to sites of scientific interest.

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USAP SURFACE-SUPPLIED DIVING

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Introduction

The U.S. Antarctic Program (USAP) has a long history of scientific diving. By taking advantage of the equipment and expertise brought to the program by commercial divers, scientific diving has benefited from the use of surface-supplied diving techniques. Safety, comfort and efficiency are enhanced in some applications by using the mode long associated with industry but rarely used in the scientific arena.

Statistics

USAP scientific diving started in 1963. Records have been kept since 1989 (a total of 154 divers logged 10,407 dives to date). Since 1992, USAP has supported surface-supplied diving. In that period 459 surface-supplied dives (of 8,441 total dives) were logged by 32 divers (of 107 total divers). The vast majority of surface-supplied dives were performed by 8 divers.

Origins

As early as 1978, Drs. George Simmons and Bruce Parker had divers in the McMurdo Dry Valley Lakes using KMB-10 bandmasks. These dives were done with a communication line but air was supplied from scuba cylinders worn on the divers back. With the ability to communicate with the surface, divers worked solo sampling the algal mats. A suited standby diver was maintained on the surface.

In 1984, a handful of surface-supplied dives were made by Dr. David White's project in McMurdo Sound. Greg Stanton, a member of that group, experimented with injecting a hyper-saline solution into a modified hot water shroud on a KMB-10. He felt this would reduce equipment freeze-up problems. This use of surface-supplied diving was of limited success. The majority of the dives for this project were done on scuba using the standard USAP equipment of the day, U.S Divers Royal Aquamaster double-hose regulators. All of these surface-supplied dives were made in buddy pairs with the second diver on scuba.

No information is available on the training provided to these science groups in the use of surface-supplied techniques or bandmasks.

1992 saw the beginning of several projects studying benthic pollution in the contaminated water of Winter Quarters Bay and around the McMurdo outfall. Initial sampling was done by USAP commercial divers who were working at McMurdo. Scientific divers, anxious to see the study site and use the diving mode began diving with the commercial divers to complete the sampling requirements. All diving was done with program-supplied commercial diving equipment.

Although many individual divers with these projects made one or two surfaced-supplied dives, the majority of dives were done either by commercial divers or the few scientific divers who were interested in the diving mode or had an aptitude for the work.

Training these scientific divers amounted to little more than a short, hands-on briefing on the operation of the dive helmet and emergency procedures for loss of surface air, loss of communications, and basic line-pull signals.

Current USAP Surface-Supplied Scientific Diving

In addition to contaminated water operations, surface-supplied diving has found other niches in the USAP diving repertoire.

Surface-supplied diving is now the exclusive mode used by USAP divers operating in the Dry Valley Lakes. Environmental protocols mandate the use of solo divers to minimize disruption of lake haloclines. Safety concerns demand that solo divers using relatively unreliable band- or full-face masks be provided with a large supply of breathing gas. Prior to 1999, solo dives with scuba and tethered communications was the standard operational mode. That year an experienced full-face mask diver very nearly exhausted his gas supply prior to regaining the access hole when his EXO-26 had a major free-flow problem late in the dive. USAP experience with EXO-26 masks has been 11 free-flows in 106 dives (10.4% failure rate). AGA masks have had 2 free-flows in 26 dives (7.7% failure rate). These data come from dives in the Dry Valley Lakes where water temperatures range between 0°C and 2°C. It is assumed that failure rate would be even higher in -1.5°C water of McMurdo Sound. Specific failure rates for either the Heliox-18 or Superlite-17 helmets cannot be gleaned from the USAP database, although it is felt to be similar to the full-face masks.

Surface-supplied diving is also being used to gain efficiency in some sampling operations. Dr. Sam Bowser studies benthic foraminifera at New Harbor on the western side of McMurdo Sound. Sampling consists primarily of using an airlift to dredge the top ±1 cm of the sea floor. When done on scuba, two divers are required in the water so that one diver can airlift. On surface supply, one diver is in the water at a time thereby doubling the work that can be done for a given hyperbaric exposure.

Surface-supplied diving is used when workloads demand higher respiration rates that can be supplied by scuba. A benthic pollution study currently being conducted by Dr. Mahlon Kennicutt requires coring in an area of frozen sediment. It is difficult to imagine being able to effectively do this on scuba. At other sites for this study, a large number of cores are required at 120 fsw. Being able to work fast, with inherent high respiration rates, means being able to reduce the number of dives required to complete this sampling.

Once a mobile surface-supplied diving system is set up, deployment of divers is much faster than with scuba. This makes use of this mode ideal when making short dives at multiple sites.

Training

No structured training course exists within USAP for surface-supplied diving. Scientific divers are trained as needed, one-on-one by the USAP Dive Supervisor. Both the Woods Hole Oceanographic Institution (WHOI) and Catalina/National Undersea Research Program (NURP) surface-supplied diving curricula are utilized as training aids.

Training topics include:

- System set-up
- Introduction/familiarization with bandmask/helmet
- Out-of-air emergencies
- Tether management
- Line pull signals
- Free-flow procedures
- Equalization
- De-fogging
- Decompression requirements
- Tending the surface-supplied diver

A minimum of two familiarization dives are made by each new surface-supplied diver under the direct supervision of the USAP Dive Supervisor. It usually takes two days to accomplish all topside and underwater training. Often, working scientific dives are made on the second day.

Crew

A three-person crew is the minimum personnel requirement for USAP surface-supplied diving. The positions include a supervisor/tender, a diver, and a suited standby diver. The standby diver can use either scuba or surface supply. A second tender is recommended but not required in our organization. In practice, there are usually a number of people available at the dive site to lend assistance.

Equipment

The USAP scientific diving program shares equipment used by commercial divers at McMurdo Station. In this way, a variety of specialized equipment is available to the scientific community with the cost either shared or completely borne by the commercial operations. A variety of bandmasks, helmets, umbilicals, dive control panels, communication systems, bailout harnesses, compressors, and HP air delivery systems are currently available in the McMurdo dive locker. The planned future addition of a hot water system will further increase opportunities for the science community to utilize techniques usually limited to the commercial sector.

Currently, the majority of surface-supplied diving is done utilizing HP storage bottles as an air source. A large 35 cfm/150 psi diesel compressor and smaller 14 cfm/125 psi gas compressor are available but rarely used for scientific diving operations.

Permanently mounted on the dive locker PB-100 track vehicle are two fully plumbed 281 ft^3/2265 psi cylinders. Quick disconnect fittings allow the stored air to be easily connected to the dive control system or the dive locker compressor. The PB-100 is also set up with a dive umbilical so that operations can be conducted directly from the vehicle. A small towable fiberglass structure is often used. An access hole in the floor allows diving to take place directly from the hut, thus protecting the dive team from the elements.

Across McMurdo Sound at New Harbor where regular surface supplied-diving operations take place, a single 445 ft^3/2400 psi cylinder is used to supply diver's air while a second 445 ft^3/2400 psi cylinder is used to power an air lift. Air is regulated directly at the bottle and a small portable communication system is used. No dive control box as such is required. This system is usually set up inside a structure on the ice that provides an access hole and houses the portable HP compressor used to charge the large storage bottles and well as scuba cylinders.

A small portable HP System is set up for use in the Dry Valley Lakes. Two 281 ft^3/2265 psi cylinders are set up on a pallet, and a single diver control and communications box is used. A portable HP compressor is on site to charge the cylinders. This system is easily transportable via helicopter sling load.

It has been our experience that divers new to surface-supplied diving transition better from scuba if a floating umbilical is utilized. Not only does a floating hose help the new diver avoid fouling on bottom obstructions, it also eliminates disturbance of the benthos. Umbilicals with an Aqualite air hose, Synflex pneumo hose and Milspec AS418 communication/strength member are found to be cost effective and provide enough buoyancy to float in seawater. For use in the Dry Valley Lakes, a slightly more buoyant spiral Aqualite air hose, Aqualite pneumo hose and JDR polyester/polyurethane communication cable is used. These umbilicals are more expensive but are required to keep the umbilical off the bottom. They are also significantly lighter in weight, which is important for helicopter transport.

USAP uses Kirby-Morgan Heliox-18 bandmasks and Superlite-17 helmets. While these units have a greater propensity to freeze and free-flow than our issue Sherwood Maximus scuba regulators, their track record is as good as either the EXO-26 or AGA Divator full-face masks.

Costs

Minimum required equipment for a single surface-supplied diver:

1 ea	Bandmask	$3135
1 ea	Umbilical, 300’	$2250
1 ea	Bailout Harness	$528
1 ea	Dive Control System w/comms	$3975

Hot water can be added with:

1 ea	Hot Water Heater	$6681
1 ea	Hot Water Suit	$2270
1 pr	Hot Water Boots	$156
1 ea	3mm Wet Suit	$132
1 ea	Hot Water Hose, 300’	$267

Conclusion

The U.S. Antarctic Program has found that surface-supplied diving benefits the underwater researcher in numerous applications. Scuba is still used for the majority of USAP scientific diving but the use of our surface-supplied system is becoming more and more popular as researchers become familiar with its capabilities and comfortable with its operation.

DEEP SCIENTIFIC DIVING IN EUROPE: IDENTIFYING THE NEED

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Introduction

Although the technical and physiological ability to dive to depths of between 50 and 90 metres (165 to 300 feet) has been present in Europe for many decades, it is only with the adoption of such diving depths by the recreational sector has the necessary training and equipment become available to diving scientists and archaeologists at acceptable costs. Whereas there are considerable concerns that any adoption of recreational techniques could compromise ‘at work’ safety when applied at depth, there is some discussion within Europe that advocates that similar practices that are employed by leisure divers for diving deep could afford methods for extending underwater scientific and archaeological exploration. The counter argument is that many of the newer technologies that are aimed at the recreational market are to some extent unproven and that, if the need is great enough and can only be achieved through diving, scientists and archaeologists should be employing tried and tested diving techniques such as surface-supplied or even saturation diving. Driving the whole of this debate is what the scientific or archaeological needs for working at depth are. In many cases, identifying the need is not difficult. However, that need then has to be assessed within the context of evaluating the potential value of that need within the context of employing conventional non-diving technologies such as ROVs, AUVs, manned submersibles, and all the various types of multibeam sonar.

This paper examines the scientific and archaeological need for deep diving within the context of the present capabilities and opportunities. For the purpose of this review, deep diving is defined as being between 50 and 90 metres (165 – 300 ft).

Deep Diving in Europe

From the mid- to late-1960s the main concentration of diving at work operations at depths equal to or deeper than 50 metres (165ft) have occurred in the North Sea in support of oil and gas exploration and exploitation (Limbrick, 2001). In the North Sea, the 1960s to the early 1980s saw a period of remarkable innovation and experimentation in deep diving, sometimes at high human cost (Warner & Park, 1990; Limbrick, 2001). However, by the early 1980s, fatalities in the North Sea were becoming rare and established methods of routinely working safely at depth had evolved, which included the combined use of mixed gases and saturation diving.

There has always been a military requirement in Europe to maintain a deep diving capability although the operational needs and depths often remain confidential. This notwithstanding, the increasing reliance on proprietary equipment suppliers indicates that a maximum operational depth of 120 m (400 ft) may be close to the present specification (*e.g.* www.divex.co.uk).

Since the mid 1990s there has been a steady increase in the amount of deep diving undertaken by recreational divers in Europe. Some of this increase can be attributed to the advances made with regulator and dry-suit performance, which in turn has made diving to depths in excess of 50 m, while using air alone, more accessible. However, at the same time, recreational organisations began to offer advanced or technical dive training in disciplines such as extended air range (diving greater than 50 metres on air but decompressing on oxygen-rich nitrox mixtures) or trimix (oxygen, nitrogen, helium) diving. The later introduction of computer-controlled constant or variable oxygen partial-pressure rebreathers continued to make depth more available to the recreational diver.

Being unregulated, it is always difficult to estimate the volume of recreational deep diving undertaken. In an analysis of recompression incidents off the west coast of Scotland, Sayer & Wilson (2006) present trends for the maximum depths of the incident dives from divers who have been treated for decompression sickness. Although the average depth of incident dive varied little over the 35 years of analysis (1972-2006), no incidents of decompression sickness were seen in recreational divers diving deeper than 50m before 1995. Since then, fifteen divers have been treated whose incident dive depth was equal to or deeper than 50 metres with an annual incidence rate of between 0 and 13% of all treatments (ignoring fatalities). Nearly all of these incidents occurred when the diver was breathing air at depth with only one case of using trimix (at a maximum depth of 91m, 300ft). A number of studies have attempted to calculate the incidence rates of decompression sickness for different diving sectors and estimates range from 0.06 to 0.49 cases per 1000 dives (Arness, 1997; Gilliam, 1992; Wilmshurst *et al.*, 1994; Trevett *et al.,* 2001; Sayer & Barrington, 2005). Combining these rates with the incidence rates of decompression sickness per year in divers diving equal to or deeper than 50 metres from Sayer & Wilson (2006) suggests that, for years when there were treatments from those depths, the levels of deep diving on the west coast of Scotland could vary between 2000 and 67000 dives per year.

Regulating Diving in Europe

Within the scientific diving sector, that in many countries also includes the archaeological diving community, there is huge variation in the degree of regulation for diving at work activities, and within this shifting regulatory framework, there are few specific regulations concerning the maximum limits of diving and/or the types of diving. In general, there is a fair degree of differentiation between the regulations governing scientific diving operations carried out in northern/Atlantic-coast Europe compared with those undertaken in Mediterranean Europe. It is largely probable that many of the regulatory differences are related more to the relative ambient diving conditions than any specific nationalistic differences but, in general, regulation tends to be more prescriptive in northern Europe. That notwithstanding, there are significant differences in approaches to regulation in European countries that share common boundaries and seas.

In 1997, the UK Health and Safety Executive (HSE) introduced, in close association with the relevant diving at work sectors, generic diving at work regulations with sector-specific guidance that replaced highly-prescriptive legislation with "goal-setting" or "competence-based" legislation (HSE, 1997). From the standpoint of scientific diving at depth, there is no guidance as to what would be considered a safe depth or what would be considered a safe approach to diving at depth. The basis of "goal-setting" or "competence-based" approaches to managing diving at work operations is that it transfers the requirement for certified evidence of ability from the regulating body to the requirement to prove competence on the operational group. The consequence of this approach is that it permits diving groups to dive to any depth using their preferred approach as long as they can argue and support "competence". Although the UK HSE can suggest best practice, in the UK "goal-setting" legislation is only clarified through judicial outcomes from related cases. The UK situation contrasts with some other northern European countries where prescription still exists. A current example is Eire, where some isolated fatalities have culminated in some potentially extreme legislature that could limit maximum diving depths to 30m (100ft).

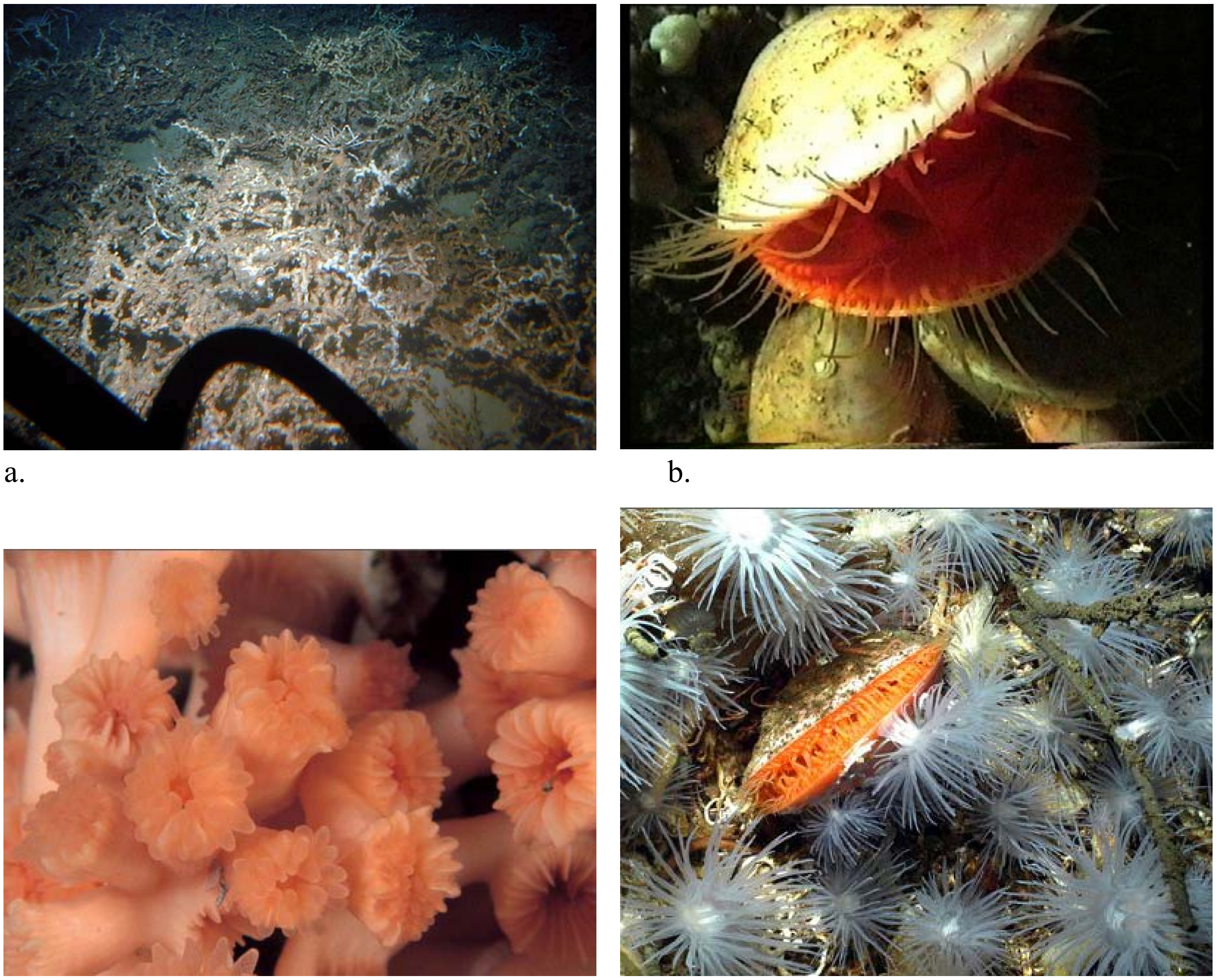
A scientist or an archaeologist who operates within a country that permits a more open "competence-based" approach to self-regulation would not be limited either by depth or operational design as long as they could support their planned operation within industry-recognised standards. This is the present situation within the UK where the emphasis remains on proving competence but with limited guidance.

The Scientific and Archaeological Need For Depth

The recreational and offshore sector/market suggests that there exists a logistical capability for working at depth. In addition, in some European countries there is either no legislation or there is competence-based legislation, that would permit deep diving for science and/or archaeology using the full range of permissible equipment and/or gas mixtures. Given this relative depth and equipment independence, what are the main research priorities within scientific and archaeological European diving that may exploit the present legislature?

Cold water corals. Most records of the azooxanthellate cold-water coral *Lophelia pertusa* (L.) are in the north-east Atlantic (Wilson, 1979; Rogers, 1999; Roberts *et al.,* 2003). Although predominantly found in very deep water (>100m) there are records of this coral occurring frequently within the depth range of 50-100m (165-330ft) (Mortensen *et al.,* 2001; Fosså *et* al., 2002; Roberts, 2002; Roberts *et al*., 2005) which would be in the range of scientific divers employing deep diving techniques. The visual records of these coral communities range from low-resolution underwater television camera footage from ROVs to the high-resolution photographic records made by divers (Figure 1).

In addition, to the enhanced biodiversity associated with these cold-water coral reefs, it has been suggested that bivalve molluscs that are closely associated with cold-water corals may offer an extremely accurate proxy for paleoenvironmental study (*e.g.* Correa *et al*., 2005). However, the ability to remove specimens of the bivalve *Acesta excavata* using ROVs with manipulators without causing damage is doubted. The use of deep-diving scientists would be the preferred method of obtaining specimens.



a. b.

c. d.

Figure 1. A comparison between photographic records obtained in deep cold-water coral reefs taken by ROV (a & b) and diver (c & d). All photographs are taken in water of depth greater than 85 metres (280ft). Photographs reproduced from www.UWPhoto.no.

Submerged Landscapes. When the Earth warmed 10-15000 years ago, following the last northern hemisphere "Ice Age" there were two consequences as far as the sea level of the north-east Atlantic was concerned. Firstly, and obviously, there was an increase is seawater volume that produced a relative rise in sea-level. However, there was also a concomitant readjustment of the terrestrial profile in relation to sea level caused by the reduction of ice mass resting on the land mass. Prior to this readjustment, the UK was joined physically to the main European land mass. As sea levels rose because of the melting of ice, and the western edge of Europe sprung upward in response to the lessening of the weight of ice upon the land-mass, the North Sea and much of the English Channel flooded. The employment of sub-surfacing profiling has demonstrated that, where this pre-submergence landscape existed, that there are paleo-channels that delineate where rivers and deltas existed in the past. With flooding, areas of the south coast of England and the North Sea are now submerged between 20 and 120m of seawater. A topical major objective for marine archaeologists is both to map and investigate these submerged landscapes that may offer up untouched examples of life in ancient Britain during and after the last Ice Age (Flemming, 2005: Figures 2 and 3)

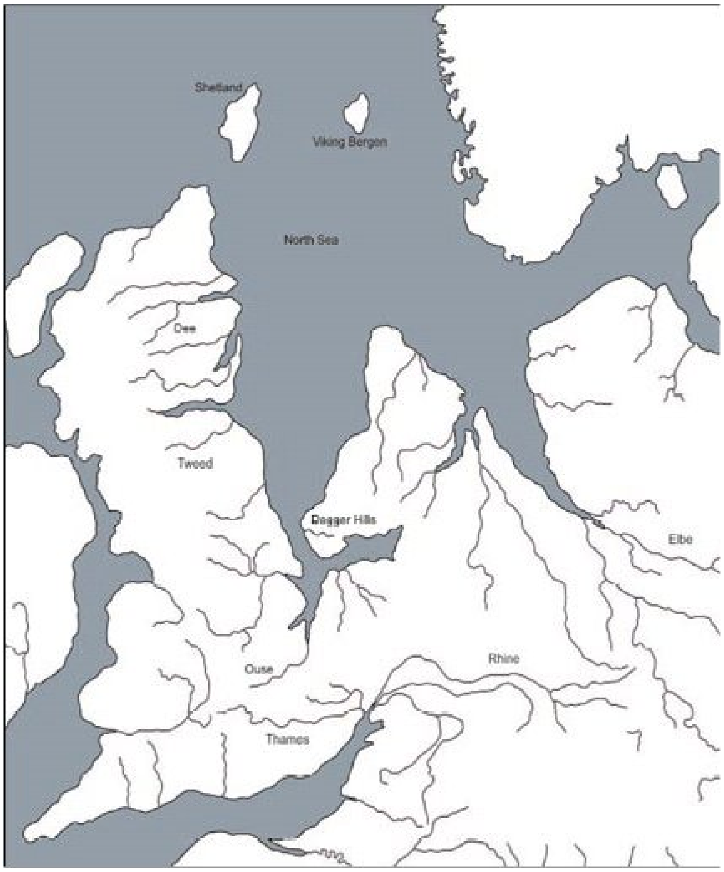


Figure 2. The paleoriverine system of the North Sea, 10-12,000 years ago (Flemming, 2005).

Deep Sea Lander technology. The exploration of the deep-sea environment is being revolutionised by the employment of autonomous or semi- autonomous Landers (Figure 4; Bagley *et al.,* 2005). Just as in the same way that inter-planetary Landers are dispatched to remote environments to collate and/or relay information, deep-sea Landers are being sent to examine the deep oceans. Throughout the historical development of deep-sea Landers technological advances have been compromised through the inability to imitate deep sea pressures when validating physical measurement mechanisms (Bagley *et al.,* 2005). Invariably, the validation experiments have been undertaken in seawater shallower than 30m in order to maximise the use of divers to record, observe and measure Lander performance. However, there are examples where a Lander verified as performing well in relatively shallow water has failed in deep water. It would be more instructive to examine Lander performance closer to the actual depths of deployment by using deep diving techniques.

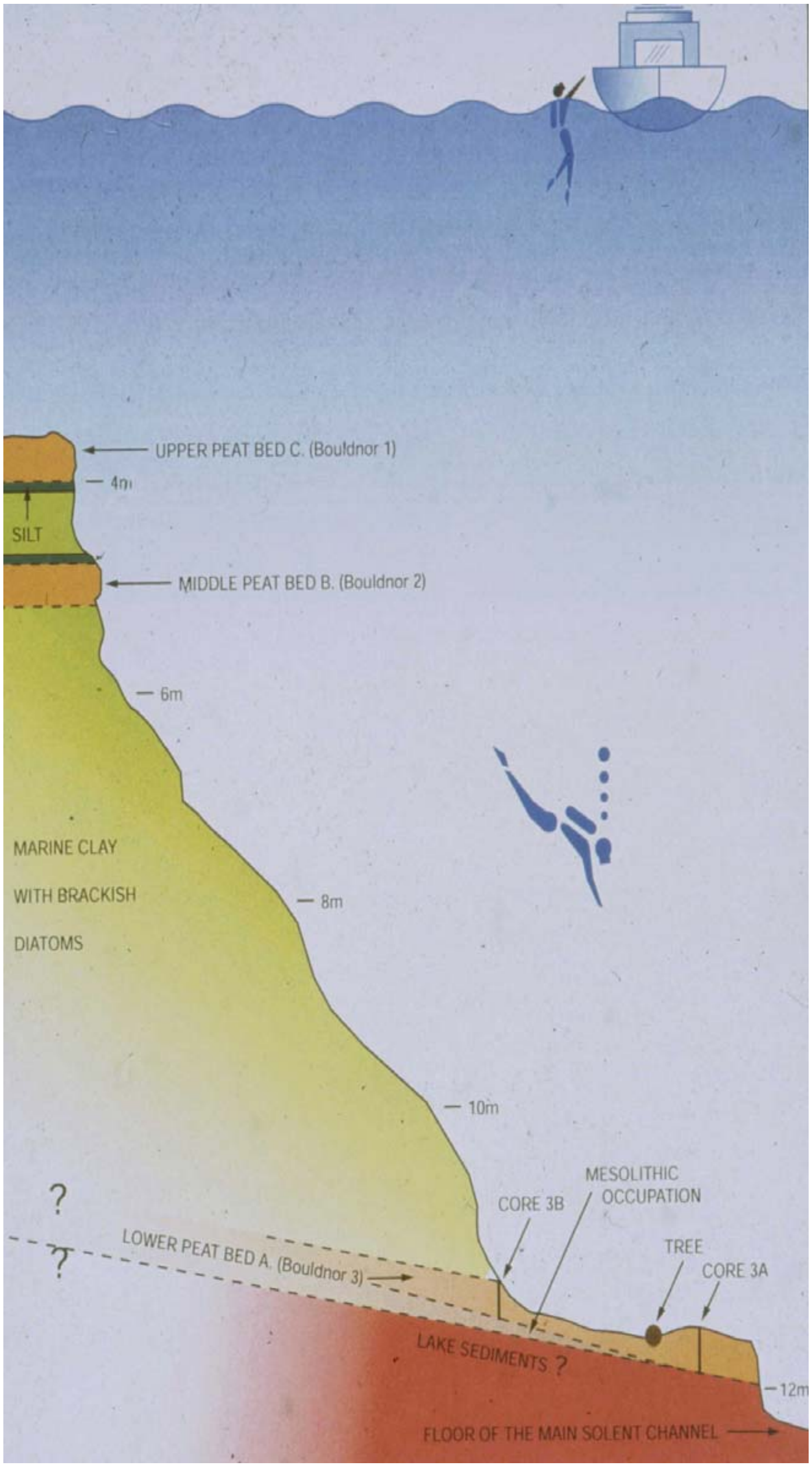


Figure 3. A diagrammatic representation of a submerged landscape. (reproduced courtesy of Dr Garry Momber, the Hampshire and Wight Trust for Maritime Archaeology)

Figure 4. A semi-antonymous benthic lander being deployed into deep water. (reproduced with permission from Duncan Mercer, Scottish Association for Marine Science)

Discussion

In Europe there is an established recreational and occupational capability to dive within the proposed scientific operational depth range of 50-90m (165-300ft). However, for divers who are at work in Europe there are varying regulatory constraints relating to the need for deep diving (> 50m; 165ft). Some of the national regulations would and do permit deep diving using mixed gases and rebreathers and so the technological basis for the expansion of scientific and archaeological diving into deeper waters presently exists. This notwithstanding, there needs to be robust and valid reasons for scientists and archaeologists to dive deep and these reasons need to be matched against the capability and availability of present-day deep water technologies such as ROVs. Scientific and archaeological research into cold-water coral reefs and submerged landscapes, in addition to the technological validation of autonomous and semi-autonomous deep-sea Landers, seems to offer these reasons and may act as the catalyst for establishing deep diving teams in Europe. However, any expansion into deeper waters would have to be risk managed. Current trends in scientific diving show that the vast majority of dives (>80%) are undertaken in the 10-30 metre (33-100ft) depth range and only 2% being deeper than this (Sayer & Barrington, 2005). This type of diving has produced incident rates of less than 0.06 per 1000 dives (Sayer & Barrington, 2005) and it remains to be seen as to whether the regulatory bodies would continue to allow diving in excess of 50 metres (165ft) if incident rates became higher than those that have been established within the scientific sector.

Acknowledgement

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3. Comparative Operational Experience Discussion Session

B.Stinton: Before you could go to the USN diving school in the past you had to take an O_2 tolerance test. Do they still do that?

D.Southerland: No. If you had a convulsion or symptoms on your first oxygen tolerance test you were kicked out of the program. However, if you made it through that and then the next dive you made you had a convulsion, there was no issue. It turned out the test wasn't very predictive. Decompression modeling is an exact science compared to oxygen toxicity modeling.

M.Lang: The risks of short deep dives versus long shallow dives in terms of dysbaric osteonecrosis is not clear. In terms of Charlie Lehner's work and others, we're leaning more towards watching out for this 50-60-foot range for hours on end, day after day, week after week, versus these short 190-foot spikes where you end up with a total bottom time of 30 minutes, including the ascent.

M.Gernhardt: Regarding yo-yo diving possibly increasing the risk of Type II DCS, do you have any statistically significant data supporting that?

JP.Imbert: No, I have no data that I can refer to, except that in thinking about the problem related to deep excursions from saturation diving, you're certainly aware of the literature about it. I remember an experiment run at Comex where they had high altitude excursions. They could do it once, they could repeat it the following morning, but the second day they had severe vestibular events. It's a similar phenomenon, linked to the residual bubbles.

M.Gernhardt: The reason I ask that is we implemented a procedure in commercial diving that we called the hang-off procedure, and if you were working on the bottom and a problem with the rigging occurred, we could come up to 30 feet as long as our first stop wasn't at 30 feet, and we could hang off there for up to 20 minutes up to three times. It was a little bit more complicated than I just explained, but we did that a lot and we never had any DCS on those dives. I have a theory that intermittent recompression during decompression is actually a good countermeasure to decompression stress, and there's recently some altitude laboratory exposures from Brooks Air Force Base that suggest an advantage of that.

JP.Imbert: Yes, it's surprising and the same experience for me. In recreational diving you have a procedure if you were ascending accidentally to the surface, you should recompress and spend five minutes, and it definitely worked. On the other hand, when I was working at Comex with data from a diver working in the southern part of the North Sea, which is shallow in front of the Netherlands, we know for sure that he was working on sandbagging the pipeline. He spent the day going up and down to the work site in just nine meters. By repeatedly ascending and descending he was able to develop Type II DCS, and it's just because he was bounce diving and yo-yo diving. There must be an individual susceptibility and a dose response. It must be also something related to the size of the bubbles.

W.Gerth: Dick Dunford has published a study of VGE incidents in recreational divers over the course of multi-day diving and has documented that the VGE actually decrease over the course of multi-day repetitive diving, they do not increase. David Doolette has published similar findings for repetitive dives. The contention that multi-day repetitive dives get more and more risky or the repetitive dives are more risky than the original first dive is an issue that's subject to some contention.

JP.Imbert: I'm aware of similar data. It’s very confusing. Basically, if you're shallow you can do a lot, if you're deep there's little you can do. Dr. Fructus, who designed most of the tables at Comex, used to remind me that he designed the 1974 table for Comex and he did the first dive and the second dive somehow successfully. Suddenly he just wanted to try to do a third dive in the day. He said when he was shallow he was okay, but as soon as he reached deeper depths, 42-45 meters, after the first dive, the diver couldn't even walk out of the chamber. It’s definitely something we don't understand. It might be related either to the dose or to the size of the bubble or to the gas.

A.Brubakk: I will not comment on the multi-dive data because that's obviously quite complex, but we have done experiments where we have performed intermittent compressions at the stops for U.S. Navy type dive profiles, and we saw a significant reduction in venous gas bubble formation, which we used in order to document that it actually is a bubble phenomenon because you wouldn't expect that.

K.Huggins: On the quarter-inch umbilical you're talking about, is that just the gas supply line, or is that the entire umbilical with strength member, comms and pneumo?

M.Ward: We built several systems and sold a few to the Navy, but they’re air systems using quarter-inch umbilical. We've been dealing with the mixed gas side of it, and it's doable, certainly to 250 feet. I haven't really tested with it deeper than that, but we do a little bit of cheating with the system. For all practical purposes it's surface-supplied scuba. We're sending 350-400 psi of gas down to the diver, and it's re-regulated at the diver. In the event you had an emergency, you'd go from your semi-closed circuit to open circuit. Certainly down to 250 feet performance wouldn't really be an issue. There are many regulator systems that can handle that. But, when you start going deeper than 300 feet, you're going to start exceeding the limits of that capability. It does make a difference when you dive a lightweight surface-supplied system as compared to trying to do it with full heavy gear.

M.Lang: What engineering changes do you need to make to a Superlite-mounted regulator to not affect the work of breathing and resistance at 300 feet versus 200 feet?

M.Ward: Diving off a normal air compressor, the output is about 190 psi. For instance, in the Gulf of Mexico, they run 5120 Quincys, which is the standard compressor. They put out about 80 cubic feet a minute at 190 psi. The problem is when you get to 200 feet, you've got less than 100 pounds over bottom pressure. The performance of the helmet goes right out the window. It's fine as long as you're not doing any heavy work, a breathing rate below 40 liters per minute, 40 RMV. As soon as the diver has to do heavy work, he must go to free flow. The concept behind this quarter-inch umbilical is being able to get enough gas down to the diver, so we jack the pressure way up high and we re-regulated that to the diver so that he’ll be able to maintain those RMVs. In the lightweight air system that we have, a standard Superlite 37 helmet will do 75 RMV at 150 feet, no problem at all. It will actually do about 45 to 50 at 200 feet. That's where it starts to fall off at those pressures. We can do the same thing with helium because it's so much lighter. We can go a lot deeper on mixed-gas sites, certainly to 250 without a problem.

M.Gernhardt: I've done a fair amount of work in three to four knot currents off of Peru, and I was awful glad to have a hose on me so I didn't end up down in Antarctica. Was your point that scuba is better in those circumstances strictly because you're working off of small support vessels, and you can't have an open bell?

D.Kesling: If you don't have a platform or the monies to support that, what other options are out there? Self-contained untethered diving seems to be a viable tool for areas where we may be experiencing one to two knots of current and still be able to get divers to the bottom and have a productive bottom time. If it's unworkable, then it's easier, and there are situations where you're a mile and a half from the shore, but the decompression was very effortless and teams remain intact. We've got good reporting from our support divers in the water and we're just in the stream there and recovered.

M.Gernhardt: As long as you plan for that kind of recovery you're fine.

D.Long: Regarding development of better equipment, you mentioned rebreathers, communications and direction finders or location devices. Yet your complaint was about double tanks and triple BCs. Could you be more specific about what your wish list would include?

Q.Dokken: What we need is for the engineers to work with the air capacity so that we don't have two side tanks. Engineer some type of air volume pack, that is streamlined, more ergonomically correct, and easier to use.

D.Long: You're primarily talking about capacity.

Q.Dokken: Not just capacity. We want our bottom mix, which we usually carry about 180 cubic feet of, 80 cubic feet of travel mix, and another 80 cubic feet of O_2. What we'd like to see is all of that put into one package that you put on a harness instead of trying to hang it on the side.

M.Gernhardt: What percentage of your dive time are you concerned with the overhead of manually flying this rig in the context of the scientist on the bottom with the surface guys watching out for him so he can just look at the science?

K.Shreeves: Not that much. The reality of the way experienced divers manually fly these units is by checking PO_2 and learning how often oxygen needs to be injected. That's all you're doing. If I stop to take pictures, I know I'm going to lose my focus and that's when I'll actually count on the automatic more and it will be on. I have a warning light that tells me to look at my gauge if anything happens. Nonetheless, every couple minutes I'll flip up my secondary, see what it says, check my gas supply. You could do the whole dive and get a lot of work done without the automatic at all. The Electrolung model of the 1960s was just flown manually.

M.Lang: Would you further comment on the two near-fatal rebreather events that Richard Pyle experienced? He has done a good job of describing them, but these were incidents that most programs would not have been able to afford.

K.Shreeves: Yes. In fact, if you read some of Richard's paper, he does wonderful accident analysis and he'll tell you what he did that was stupid and what he did to prevent it in the future. It helps to have a very self-analytical person. In his papers he discusses something he did and thought was brilliant and then later realize that if anything else had happened, he would have been in big trouble and consequently never did that again.

C.Cooper: What's the basic cost of the Ouroboros and the PRISM?

K.Shreeves: The Ouroboros is $14,000 a unit and the PRISM is $7,000 a unit.

M.Gernhardt: One of the arguments for closed circuit is cost, which you have to look at in the big picture. What's the cost of keeping your scientists proficient to be safe with CCRs? What's the cost of their time to keep them proficient and what does that take away from the ability to do science? What is the cost to your program of an accident of any kind? Each organization might have different constraints in that regard. Just because that was the optimum solution for the South Pacific group doesn't mean that it should be applied to a broader scientific community like Smithsonian or NURP. Is your typical scientist the kind of guy who is really into his part of the science and does some diving only as a tool to collect the samples, or is he able to be a dedicated diver? This changes the consideration very much and from my background, I would rather see the control and safety from a professional dive team on the surface with communications and a hose than to put CCRs in the water. Although, I do like the notion of hybrids where you have a CCR with a light umbilical with telemetry back to the surface and some commercial decompression techniques. There's some promise in that, but it's probably a mistake to generalize and say this is the best way.

K.Shreeves: I didn’t mean to come across suggesting this is the best way, I was trying to say exactly what you just said. This is not a good technology for the part-time diver. If you have divers who can be para-scientists and can carry out research, then that will work. Divers like Richard Pyle who are doing this in support of their research all the time, then this will work. This methodology will not work for a lot of scenarios and it actually reminds me of what you do. You're a scientist who goes into space. The average scientist couldn't maintain the proficiency to do that so you carry out the research for them. If we need to get the principal investigator down to 300 feet and he's not willing to gain the experience and training proficiency, this is absolutely not the technology to use.

P.Ruden: A technical CCR problem is that you can't monitor CO_2 scrubbing efficiency, which is often inconsistent.

P.Lobel: There are two different groups of scientists, those who really just want to go for a look-see and those like Rich Pyle who say deep water is where they need to do the research. If you're going to do that research and be productive, you're going to do it on a continual basis. At least for a period of time in order to address those questions. As part of the training and standards that AAUS needs to develop is consideration of the different calibers of scientist. Not everyone's a field scientist. Lots of scientists are at home in the lab and really shouldn't be driving to work in the morning during rush hour on a busy street. There is going to be necessary support for a look see, somebody who normally doesn't go to those depths. For the most part, the scientist who's going to be successfully getting funding to do this research on a continual basis is someone who's going to have to be an expert at these systems and productive by publishing papers based on repeated good results.

M.Lang: The key point here is the nature of the underwater activity. If you're a full time research scientist in an academic institution, you are not going to get much credit in your professional evaluation every three years for spending six weeks going through a rebreather course and performing periodic requalification dives..

M.Slattery: Whether you're doing rebreather diving, closed-circuit trimix, open-circuit trimix or surface-supplied diving, you're still in need of that manual training. You don't stop your training on open-circuit trimix, which I've been doing for five years now. The same goes for the individuals with hard hats. You're not just going to show up one day on the dock and start diving again. They're going to need a similar level of training. The people who are getting into this deep diving for research are making a commitment.

M.Lang: Much also depends on the underwater tasks. This past August we had a Scripps/Smithsonian expedition to the Line Islands, south of Palmyra, where 18 scientific divers logged over 900 dives in 21 days. Had our working depth range been other than 40 to 50 feet, say 180 to 200-foot range, it would have been impossible to fly a CCR manually. The entire dive of 60-70 minutes is spent recording data, collecting specimens, or taking microbial swabs. The dive is so task loaded already by the science purpose that there's not much time left over to check PO_2. Therefore, there is a need for a bulletproof, uncomplicated life support system. The dive objective is not operating diving technology, it's gathering biological data. Open-circuit scuba happens to work well with a dive computer on your wrist. Start compromising your precious research bottom time by continuously having to look at triple redundant oxygen sensors, it's not going to work for most. The take-home message is the CCRs are not going to be a mainstream tool for every scientific diver to use. I'm sure we'll hear tomorrow about the disadvantages of surface-supplied diving, and how we cannot work being tied to a tether. However, there are many specific research opportunities right now where we could perfectly use either open-circuit trimix or heliox by hose to 300 feet.

W.Gerth: We evaluate closed-circuit rigs for the U.S. Navy, in particular the two communities they're in, the Special Forces guys and EOD. One of the sets of criteria that we are evolving is that the rig should be able to function with a diver hands-off and have it not kill them on a regular descent and ascent. One of the big problems we're debating between our sponsor at NAVSEA and us is what the PO_2 overshoot max can be during descent. In the Ouroboros, for example, the PO_2 overshoot is minimized during descent by a manual shift over. You have to shift that gas from .7 travel mix down to 1.3 bottom manually. It doesn't perform the shift automatically. If you forget, again going to hands off operation, this rig should work and not hurt the diver. Same thing with the PO_2 undershoot on ascent. You don't want to get hypoxic on ascent if you have to do a rapid ascent. Again, if you're flying these rigs manually, no problem, but you've got to be careful that if the guy gets distracted, or happens to collect research data, you don't want the rig to kill him. Right now there aren't that many rigs out there that will meet that criterion.

J.Godfrey: Regarding training time, we've heard ten days for trimix, two weeks for rebreather training up to trimix. What are we looking at for trying to train scientists using surface-supplied diving?

M.Gernhardt: We had a case working with NURP where we took astronauts that were not experienced divers and did a two-day training course with them, which they did fine as long as the NURP guys were supervising the operations. I use their Aquarius saturation program as a perfect example. You wouldn't take these marine scientists and say go down, here's the keys to Aquarius, knock yourself out, and go on a sat dive. I see an analogous capability with surface-supplied heliox diving where you've got a professional team that has the core competency, and then you bring people in to do specific missions and you probably have at least a week training, in my opinion, but it depends on your prerequisites for entering the program.

M.Lang: I would reply similarly and Rob Robbins will present the under-ice surface-supplied diving we do in the Antarctic. When we did the waystation interim science program in Catalina in 1985-1986, the scientific diver training to use surface-supplied diving consisted of a two-day program in the use of tethers, masks, deco, comms, etc. Everything was controlled by Jack Baldelli and an experienced commercial crew. I'm looking for the most parsimonious, easiest transition to get a scientist from open-circuit compressed air scuba down to 300 feet. Similar to our 190 fsw profiles, I envision a short time spent at maximum depth of 300 fsw and then working your way up the reef wall. The easiest transition, in my opinion, based on considerations of training time investment and the availability and reliability of rebreathers, is by lightweight surface-supplied hose.

G.Beyerstein: Do any of the CCRs have the ability to telemetry their readings to the surface and have some sort of control on the surface?

K.Shreeves: Not that I know of, but I don't know why it wouldn't be possible.

G.Beyerstein: Hybrid technology might be a good answer.

M.Ward: Telemetry is possible, there are several ways to do it. It would actually make more sense for scientific divers to look at incorporating surface-supplied gas with the semi-closed circuit rebreather, because it's such a simple unit. You really don't need to worry about the CO_2 side of things providing the rig has a duration at the temperature you're using it at. As far as the diver having to fly it, the only thing he's going to have to worry about is when he leaves the bottom. Other than that, it'll pretty much take care of itself.

G.Beyerstein: Chris Lambertsen had a patent for a semi-closed rebreather that was never produced that has probably expired now. It had a counter lung, a mass-flow valve for your oxygen constant demand, and a mechanism whereby the most CO_2-laden part of your exhalation was allowed to bubble off to the surface.

B.Morgan: Why 300 foot in particular? In Europe you can't go beyond 150 foot without a closed-bottom bell. I really think the surface-supplied, semi-closed rebreather is a package on the diver where the surface supervisor can switch over and control the diver's mix and receives the telemetry over wire. That will work.

G.Smith: The 300-foot was an interim depth, our goal being 650 feet. We were looking for something that was beyond what we are doing now and that was a practical goal that looked achievable. I really thought in a month we could be surface-supplied diving to 300 feet if we had to. I also know that if Doug Kesling and his group are running the project, they can open-circuit dive it safely. But the idea is we want to look at all of those and be able to offer options, the best one that fits the job and the party. Eventually, we would have the money to be able to support somebody at 650 feet.

B.Morgan: The main thing you have to look at in making some of these decisions is what can an untethered diver do that a tethered diver can't do. A tethered diver gives you a coherent, one-atmospheric brain on the surface monitoring every move the diver makes. At the push of a switch he could put him on open-circuit amongst many other things that come to his help in ways that a buddy diver can't.

G.Smith: You've got a point there and as a sponsor-manager, I have to agree with you.

M.Lang: Control of the diving operation is paramount in scientific diving. The steep learning curves of the dives that Richard Pyle, John Earle, and Dave Pence did, by the way, were not under the auspices of an AAUS controlled program. These were dives done for years on their own time and gear on weekends. These divers are not employed in Hawaii as full-time research scientists, they hold other full-time positions. In general, it becomes very difficult to invest that amount of time in the technology and the training and maintain a full-time productive research career.

JP.Imbert: There's a new program called triox that an agency has proposed. It's based on the idea that the mix is high in oxygen, like 25% percent, it looks like a nitrox, and also contains 20-25 percent of helium. It has some benefits and is very inexpensive. The beauty of the system is that you can blend it directly in the inlet of the compressor so you can fill any cylinder regardless of the oxygen safety problem. You can use a table without any decompression gas, meaning that you can just dive in with a preset table or computer. You don't have to change anything to your equipment because you use the same regulators and cylinders. The drawback is that it models trimix diving. It's limited to 45 meters, but it may be useful sometime to us.

M.Gernhardt: Does anybody have a decent feel or even real statistics on the fatality incidents of closed-circuit rebreathers? I've heard of 13-14 deaths, don't know how many dives they do.

M.Lang: Dave Sawatzky reported in 2001 that there had been 9 deaths on the Inspiration (over 1,000 units in use) and many more deaths on other kinds of rebreathers. All of the deaths on the Inspiration had been due to diver medical problems or diver error and not due to malfunction of the rig. However, some of those divers were extremely well trained and highly experienced.

M.Gernhardt: That's important because if you contrast that to the commercial diving records of the big companies at Ocean Systems and Oceaneering over a decade we logged 30,000 dives a year with no fatalities, maybe one bend in a thousand dives. There's a huge difference in both the probability and the consequence when you compare these two forms of diving.

P.Lobel: Many of these early rebreather dives are being done by people on the side on their own without training or control.

4. General Discussion Session

A. Discussion of papers

L.Somers: Of the organizations that went beyond 150 feet, do you have any idea of how many of them have on-site chambers?
B.Dent: No, but I could venture a pretty good guess. It's not anything that's reported.

M.Lang: Regarding the statistics and stage decompression standards, a scientific diver who uses a dive computer at some point has a ceiling showing up on the screen. This can indicate that you're going to have to make an obligatory stop somewhere in addition to a safety stop. That fact needs to be incorporated into the overall AAUS statistics reporting. Many of these dives are decompression dives, and we need to find a way to best report them. The science community has largely moved away from the tables and their maximum depth and total bottom time entries. These "shells" of dives are meaningless (unless they're square wave) and don't allow us to evaluate the multi-level dive profiles. We're interested in a graphical reporting scheme of the dive profiles that more closely approximates what the divers are doing. AAUS needs to review the dive data submission requirements and eliminate tracking those categories that aren't going to be analyzed. There needs to be an AAUS objective or question we're trying to answer with defined dive data collection. There is a shifting baseline from the days where there was vast experience by many scientific divers writing the standards for compressed air scuba. We now have minimal experience by very few scientific divers writing the standards for rebreathers, trimix, and surface-supplied diving technologies. This results in an approach where we don't have a lot of data and background to base the writing of standards on.

P.Lobel: Part of the problem with data entry and collection is the standardization of within-institutional reporting. A general need of the scientific community is probably a standardized format software package.
M.Ward: At DiveLab, we've been doing standards work with the European CE and we also are writing the CE standards for the Kirby Morgan equipment. The European standards have one for open-circuit demand systems and one for free flow systems. Those two standards cover every kind of surface-supplied diving, but don't differentiate between hookah, lightweight, or the heavy gear. The Europeans lay out standards on all the equipment individually, but they don't tell you exactly how to meet the standard. One example is work of breathing. The standard spells out the type of testing, but doesn't go into detail, leaving it open to interpretation by people with systems, resulting in people not testing the same way. Sometimes one has to write a test standard before writing a standard because this all needs to be explained.

M.Gernhardt: What was the gas mix when you had the O_2 event on the bottom?
D.Dinsmore: I believe it was at 32 percent oxygen.
M.Gernhardt: At 250 feet?
D.Dinsmore: Yes, I think so. That was probably the reason, don't you think?

K.Huggins: I was just wondering does anybody know if any submersible lockout systems are still in operation?

M.Lang: I believe the last one in science to have been the Johnson Sea-Link submersible at Harbor Branch Oceanographic Institution and the divers Tim Askew and John Reed, decades ago.

M.Gernhardt: Regarding moorings, because of all the complications with the boat and the changing philosophy at the time of the scientists, they didn't want one spot. They wanted to move around.

G.Beyerstein: Three or four hours to set a four pointer or a three point spread is not an unacceptable time, it is normal.

D.Kesling: One of the interesting things regarding moorings is that you've got to remember that the environments that the scientists want to go to are pristine coral reef environments. There are some limitations to just putting in the mooring and here that concept really fell short because of environmental constraints for the research.

J.Godfrey: Dynamic positioning on ships is going to help solve this problem in the future. You can punch a button and have divers in the water much faster without that mooring.

M.Lang: Several of the new UNOLS vessels in the fleet have dynamic positioning, they don't have to throw hooks.

G.Smith: How many days training do you think you need to train scuba divers for surface-supplied diving?

D.Dinsmore: Joe Dobarro came to us as a scuba diver and a perfect candidate for surface-supplied diving. He's a big, strong fellow, very competent and he worked out very well. He could be a commercial diver anywhere. Four days training was adequate for him.

G.Smith: How many days do you need for average divers? Can you give us an estimate?

J.Dobarro: We've had some very experienced people in the technical diving field come to work for us as surface-supplied divers. Their comfort level in surface-support equipment was just horrendous. Some divers quit on us because of the experience within 10 to 15 minutes of putting them in the water.

D.Dinsmore: We probably needed a couple of days.

M.Gernhardt: The way the training was set up for the Aquarius work we did with the astronauts, we would typically get them down there several months in advance for some pre-training. This gives us a look at them in that environment and sometimes we screen them out at that point. When they come back for the training, it works right up to the time they go offshore. You might think about how to screen people who are adaptable to this type of diving versus the folks who aren't.

K.Kohanowich: What type of research projects did you do? Were there some successful science that was done on these projects?

D.Dinsmore: One project wanted to put juvenile ocean quahog (clams) in situ in specially designed cages. We put them right up next to the wreck of the Berringer off of Cape May, New Jersey in 150 feet of water. It was a difficult time getting into a mooring that close to a wreck, but we got those down and that worked successfully. We had a good team, seas cooperated, and we had some long bottom times. We exceeded the sur-D-O_2 limits and had to actually go into sur-D-air to get the divers out, but they were fitted with hot water suits.

W.Gerth: You were rather emphatic in a couple of places in your slides saying that you had no plans to go surface-supplied diving deeper than 190 feet and yet, as I understand it, it is your organization that is under Congressional mandate now to get to 300 feet. If there are no plans to go with surface-supplied diving deeper than 190 feet, have you already decided what mode of diving you're going to use and excluded surface-supplied diving?

D.Dinsmore: I don't see the NOAA diving program going into surface-supplied diving deeper than about 150 fsw.

W.Gerth: How do you plan to get to your Congressionally-mandated depth of 300 fsw?

D.Dinsmore: Probably not with surface-supplied diving.

W.Gerth: You've already made a decision it's not going to be surface-supplied diving.

D.Dinsmore: If a NOAA scientist comes to us with a need to get to this depth, we'll have to look at something else other than surface-supplied diving, in my opinion. It might be a bell bounce system. The NOAA diving program is currently using open-circuit technical diving to 250 fsw to do those kind of dives. In my opinion, the future for us for deep diving is the closed-circuit rebreather.

M.Lang: We'll hear from Mitchell Tartt later on about the science needs for the National Marine Sanctuaries Program, a division of NOAA.

D.Long: There's a phenomenon amongst divers that crosses every population. If a diver takes training with a basic scuba mouthpiece in his mouth and has experience and confidence with it, he's reluctant to go into a full-face mask such as a Kirby Morgan band mask. If he gets trained in a Kirby Morgan band mask type of system, he's very reluctant to put on a helmet he can't pull off immediately. It doesn't matter whether they're Navy divers, civilian divers or scientific divers. That given, the technical divers are very disciplined, knowledgeable and proficient. If, on the other hand, you start introducing them to these other technologies at their home base, doing what they normally do and where the jobsite is familiar to them, then they don't really have much of a problem progressing into using the other helmets. Personally, I can't think of anything I'd rather have on my head when I'm underwater than a helmet. But it took me a while to get there because we always thought you could drop, pop, blow and go, and you're out of there. Whereas now we're in an environment, particularly at 300 feet, where that is the last thing you can do because that's death for sure. You need progressive training. In five days you can't progress a man from being barely able to swim into a saturation diver. It's a human condition that has nothing to do with the degree of science the person has been through. It's a progressive experience that needs to start early on. You're not going to do it in a matter of days or even a couple of weeks. Where AAUS' programs can really work is by bringing the people through a progression of training and familiarization as just one more little thing they're getting in to, not one new huge thing. You don't go from flying a Cessna 150 to a Boeing 747.

M.Lang: Your point is analogous to our depth progressions for deeper certifications. A certain number of supervised dives are required within the next depth range as you step down in order to be certified to those deeper depths.

D.Long: You may also have other people who are claustrophobic in which case it doesn't matter what you do to try to put that helmet on them, they want out of there.

B.Morgan: There are many different types of scuba gear and many different types of rebreathers and following that logic, there are many different kinds of surface-supplied equipment. You shouldn't take one design of equipment and exclude scuba from a particular operation.

K.Kohanowich: Have you been doing any deep surface-supplied dives under ice?

R.Robbins: The deepest surface-supplied diving we're doing is 130 foot which is our standard depth limit for open-circuit air diving. Most of the dives in McMurdo Sound are in the 80 to 130 foot range. It obviously would be a lot more complex if we're using mixed gas.

J.Wilkins: I just feel some sense of obligation to comment on cost comparisons. I’m not here to support or defend the cost of military equipment. I showed you yesterday what it does, but we were then talking about a system that provides for two divers on the bottom at 300 feet doing heavy work and providing a recompression chamber that cannot only bring them up for decompression, but also has all the gas to support a treatment protocol as well. We can fly anywhere, go anywhere and do anything. If we're talking about hose diving for a shallow-water effort, it's a phenomenally different environment. If the workshop focus is how to get scientists in the water on a surface-supplied system to 300 fsw, which is what the opening paragraphs of the introduction were, we have got to be taking a look at what it takes to get there. Certainly people can hang on a hose and get to 80 or 130 feet and that's a much simpler, less complex, and much safer undertaking than trying to take scientists and put them at 300 feet on a mixed gas rig in the open ocean.

R.Robbins: Absolutely, no question about it. My remarks didn't address the cost of the chamber that we have on station, but it demonstrates that we can get science divers on surface-supplied diving, albeit not deep, fairly easily.

M.Lang: At this stage we’re establishing the need for surface-supplied diving because we don't have deep surface-supplied experience and we have a limited exposure to surface-supplied diving in general. We'll hear from scientists representing various communities in the next session of the scientific need of getting deep, but we fully accept your remarks on cost comparisons.

B.Dent: Scientific and archeological diving are broken into separate categories. Are you determining that archaeology is not scientific?

M.Sayer: From the point of view of diving, science and archaeology are lumped together. From the point of view of the Health and Safety Executive, the U.K. looks at five different industry sectors and science is lumped together with archaeology because of the same use of equipment and diving. The differentiation can come from the source of funding. Much of the science funding originates from the scientific research councils, whereas archaeology funding comes from arts and humanities, a different funding group. However, there is what's called science-based archaeology, funded through the science route. From the point of view of how we self-regulate, there really are two distinct communities that rarely overlap apart from the industry committees.

B. Science User Groups

M.Lang: We've invited several of our colleagues to discuss their science need for a 300-foot capability in their particular field, either through projects that they are currently doing with advanced technologies, or the need for those technologies in order to enable them to pursue their research goals.

Marc Slattery, University of Mississippi

Let me start again by thanking Mike and Gene for pulling together this workshop. It's a good learning opportunity for us scientists in looking at how to extend our capabilities and our needs at the 300-foot level.

My group has been funded since 1999 by NOAA, mostly the NURP Center, but more recently by the Office of Ocean Exploration to look at extreme environments. We've been first in the caves in the Bahamas and more recently on the open wall communities, somewhere between 300 and 400 feet over the last several years. We've done a lot of training associated with that, open-circuit trimix, deep air, and more recently moved over to rebreathers. Listening to the opportunities for saturation diving has been useful.

Our first need is that the dives be safe. That's where we start and it's challenging. I agree with Quenton Dokken's comments yesterday. It's difficult to start off and train somebody over the years and by the time they're ready to work, they graduate and move on.

The secondary need is that the dives be cost effective. From these grants we typically have $20,000 to get to the field. My field team consists usually of four to six individuals. Those individuals do have to be well-trained and capable. To deal with the issues of graduate student attrition, we've partnered with a group at the University of New Hampshire. These two groups are trained, have overlapping skills, and we're able to get the four people to the field when we need them.

We then have to be able to do the science that we're funded to do. I learned very early in the technical diving business that you can't task-overload. To keep the safety issue up front, you've got to realize that you're probably going to be making more dives, frustrating as it is, to get down and do the same amount of dives that you could do on a shallow coral reef in 15 feet for 50 minutes. It has become much more important to recognize what we have to do and then get down and do that one task well and safe.

Our research looks at the ecology of these new systems. Virtually nobody had dived in some of these caves that we were in. The wall communities' depth is something people haven't reached before, so we are surveying large sections of areas. I see a problem there in terms of being tethered in any manner. But other technologies do get us down there and allow us to do that. On the reef face, we're looking for different organisms, using instrumentation, and video documentation. Oftentimes, we're carrying down traps and employing specific collection techniques. How do we get all of that gear down there? How do we make it efficient so we can collect the data we need to?

In principle, the specifics are what is the best system for your particular question where you're working. I've worked with all three of the systems that have been discussed and in certain places, some techniques are better than others, without a doubt. You have to adapt with those.

M.Lang: What is the number of trimix dives between your group and New Hampshire, and does NIUST (National Institute for Underwater Science and Technology) have any programmatic interest in furthering deep diving?

M.Slattery: We have approximately 200 trimix dives for the University of Mississippi and New Hampshire probably has a like number. If you start to add in normoxic dives in some of those other deep techniques, you might double that number over a period of the last five years. NIUST is an institute associated with the NURP community. We're more national, rather than regional, as the other NURP centers are. We do have an interest in deep diving and applying it, and the portability of the systems. One aspect of cost effectiveness is can you move your team? I've never worked with the Aquarius group because, frankly, Aquarius sits in a spot that really isn't very interesting to the type of research I do. I'd like the opportunity at some point, but until that sat system moves to my reefs or to an area that I need to work, it just doesn't make sense for me to do the training back there either. From a portability standpoint, we are looking at what we can support and how we can get it to the places we need to be. We regularly dive for NIUST surveys, the U.S. coral reefs in the Atlantic, Puerto Rico, and the U.S. Virgin Islands. We've worked extensively at CMRC on Lee Stocking Island in the Bahamas and in the Pacific (American Samoa, Hawaii, Guam, Saipan and a number of other freely-associated states.) We may dive three quarters of those reefs in any given year for our continuing monitoring and surveying. As we start to extend the boundaries from the shallow reefs and do the comparative work to the deeper systems, it becomes more important that we can get the infrastructure to those sites, including the capability of medical-grade oxygen and helium.

J.Wilkins: If you were to have a portable saturation system that you could launch at the spot you wanted to, given your experience and your anticipated future mission requirements, how long might you want to be able to maintain a saturation system over a site of preference to you?

M.Slattery: For some of the basic research questions I would love to see that system in place for one to three months. We could do an awful lot of work. Ocean Exploration has funded us for the next two years to do deep coral reef work and putting up a month of field time for six scientists each year. We have a lot that we think we can accomplish under that time period. We've got to plan for two dive teams, so there will be one team in the water in the morning and another team in the afternoon. In 30 days we anticipate 180-man days in the water.

J.Wilkins: What kind of bottom time would you anticipate?

M.Slattery: We’re down at the 300-foot level for 8 to 10 minutes, which gets us three to four quick transects and then as any good scientific diver, we work our way back up the reef. Our deco stops will include more transects. With a saturation capability we'd be down there for a length of time really accomplishing something, which would be fantastic.

J.Wilkins: Hypothetically speaking, for a dive team to do that, would you need more than one scientist diver to accompany, if you had a three-man bell and you deployed two divers at a time, or a scientist and non-scientist support diver alongside?

M.Slattery: I definitely feel that you need a scientist on those missions. We've had a number of people approach us and ask why we don't just have commercial divers do the work for us. Partially I think that my eyes in the field actually add something to the equation. One of the other needs I feel strongly about is to get our students into the water as well. Hypothetically, you could start off with a system where a scientific diver is being supported by a trained commercial diver or Navy diver.

M.Gernhardt: What are your transect lengths?

M.Slattery: With the 8-minute dives, we're trying to get 30-meter transects. We would like to do more and that's one of the tradeoffs we're getting. The degree of statistical replication is what I would consider preliminary, but we're hoping that over the course of a month, we'll get enough replicates that it would mean something.

G.Beyerstein: How do you handle the training for your people? And how often do they dive? What's your typical mission? How long between dives do these people have and do they maintain their own equipment? How do you handle all of that?

M.Slattery: I started out in caves, went through a full cave course, and have several hundred dives now. My cave diving I now get back to once a year while I'm in the Bahamas doing the other work. I take a few days and get in there but am definitely just barely keeping up my proficiency there.

G.Beyerstein: What about the rest of your dive team?

M.Slattery: Five years ago NURP pulled together a trimix training session to 300 feet where four of us were trained. In the course of that year, after the training we were on-site doing science for two additional weeks, so we developed it. I'm one of the landlocked institutions. New Hampshire isn't, but they have cold water and are under the same constraints that we are. Our continued training is done as we get back to the site. We allow ourselves about two weeks of science at the end of our trip. We start out with about a week of refreshers, working ourselves slowly down to depth. It does involve some degree of collections and other work, but we'll start out 130 to 150 fsw and then slowly get ourselves back down to a level where we're doing the work at depth.

G.Beyerstein: I'd like Michael to relate that to his stated problem about the training that he has for his scientists for these deep diving missions.

M.Lang: We have the same issue and handle it through a requalification exercise(s) or period at the beginning of a research cruise. Our Natural History Museum divers are landlocked. They travel for their work to their sites of interest, perhaps twice a year. We implemented a requalification or refresher program before they go out in the field or we spend the first days in the field doing that, acclimatizing through progressively deeper dives.

Mitchell Tartt, NOAA National Marine Sanctuaries Program

I work with the National Programs Branch at the National Marine Sanctuary Program (NMSP), a program within the National Ocean Service of the National Oceanic and Atmospheric Administration (NOAA). Michael asked me to talk about the scientific diving needs that we foresee relative to deep diving to 300-foot depths. There are two things about this workshop that struck me as being exciting. One was the notion of going down to 300 feet, it represents a significant need for us. Also, the recognition of the Ocean Action Plan and the need to conduct coastal resource management from an ecosystem perspective as this is an integral aspect of NMSP operations. I'll give you a summary of our program and where we're located to give you an indication of the diversity of issues that we have to deal with and how that ties into our need to do things on an ecosystem basis, as well as some examples of the general categories where we see deep diving capabilities supporting our program.

The sanctuary program covers areas of the marine environment with special conservation, recreational, ecological, historical, cultural, archaeological and aesthetic qualities. Through the National Marine Sanctuaries Act, the Secretary of Commerce is authorized to designate areas in U.S. waters that are of significant importance to our economy, our natural history, and heritage.

Our scientific needs come from two primary mandates: the National Marine Sanctuaries Act and the National Historic Preservation Act. We have significant legislation that drives our needs.

- The long-term conservation and protection of sanctuary resources is our primary goal and we do this through education, outreach, science, management, and through public awareness and understanding of the marine environment. Diving activities at depth bring that critical information up to the surface to show people that what is underwater is critical to what we do. You can't protect and love what you don't understand.
- Improving management through conservation science: characterization, monitoring, and research activities. That's a key component to what we do in terms of making informed management decisions.
- Helping coastal economies by keeping sanctuary resources healthy: knowing what's out there, where it is, and how natural processes affect these resources is very important.
- Facilitating uses that are compatible with our primary function, and resource protection. We're not a preservation organization. Our mission is about conservation for multiple use. We allow a wide array of activities to take place in sanctuaries. For instance, we're allowed to have cables installed across sanctuary sea floors, which involves some disturbance. That disturbance then requires some follow-up activities to understand what the impact of installing that cable was. This is one example of deep-diving monitoring needs.

There are 13 sanctuaries currently in the system with one in the designation process. Let me show you a bit about each of them.

- Stellwagen Bank National Marine Sanctuary: We've come to find a significant submerged cultural resource component with some shipwrecks recently discovered. It also has a significant biological component because of the resources and the systems that exist around that bank as feeding areas for species like the right whale.
- The Monitor National Marine Sanctuary
- Thunder Bay National Marine Sanctuary, a newly-designated sanctuary. There are hundreds of shipwrecks that are targets and that are protected within the sanctuary boundaries.
- Gray's Reef National Marine Sanctuary is a hard-bottom reef structure off the coast of Georgia.
- Florida Keys National Marine Sanctuary.
- Flower Garden Banks National Marine Sanctuary off the coast of Texas.
- Olympic Coast National Marine Sanctuary.
- Cordell Bank National Marine Sanctuary
- The Gulf of the Farallones National Marine Sanctuary .
- Monterey Bay National Marine Sanctuary is one of our largest sanctuaries.
- The Channel Islands National Marine Sanctuary off the coast of Santa Barbara, California.
- Fagatele Bay National Marine Sanctuary is our smallest, just a quarter square mile off the island of Tutuila in American Samoa.
- Hawaiian Islands Humpback Whale National Marine Sanctuary is a humpback whale sanctuary, a single species sanctuary where we're responsible for protecting the calving and mating grounds for the humpback whale.
- Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve, a coral reef ecosystem reserve, is slated to become a sanctuary that encompasses nearly 100,000 square nautical miles of ocean waters. Within our marine protected system, it is similar in size to the Great Barrier Reef.

These are very diverse marine environments in which we need to be doing research. All of these sanctuaries, except for one, involve depths greater than 130 feet and also more than 300. This window of 130 to 300 is very important to us.

Diving supports our mandated activity defined under the National Marine Sanctuaries Act and the National Historic Preservation Act. As part of NOAA, we conduct our diving under the auspices of the NOAA Diving Program. Of the 500 NOAA divers, within the sanctuaries there are approximately 75. A significant component to what we do also relies on partnerships with other organizations: NURP Centers, U.S. Navy, universities, and volunteer divers are all resources that we try to tap into to meet our diving requirements. In the sanctuary program, we're not really looking to develop the capability to do this kind of diving ourselves. We do have platforms that can support these missions once we work with the NOAA diving program, but of those 75 divers, there's only a handful that are truly capable of doing these deep dives and participate in these activities. We are looking to understand these technologies enough so that we can effectively manage the projects that take place in our sanctuaries. It's an essential component of our ability to understand, manage, and protect the resources in our sanctuaries and understand the systems that we're trying to influence.

Here are a few examples of areas where diving to depths of 300 feet would be very useful for our program.

<u>Submerged Cultural Resources</u>: Deep diving can support our programs in submerged cultural resources. The issue of mobility and untethered systems is important in performing archeological surveys around wrecks, target verification, artifact recovery, and exploration of submerged cultural resources. There are vessels, heritage sites, old civilian sites, and civilizations on the bottom in our sanctuaries that all need to be studied and surveyed. The Portland (Stellwagen Bank), the Monitor, the Monossette (Thunder Bay) and the U.S. Macon (Monterey Bay) are examples.

<u>Habitat Characterization</u>: Habitat characterizations and assessments take place at all of our sites. We have been doing this using remotely sensed data, ROVs, and AUVs to date. However, the importance and benefits of putting a trained scientific eye right down next to those resources is invaluable. It brings to light information that's difficult to get with AUVs and ROVs. Documenting bottom type diversity and abundance, sample collections, photo and video documentation for future analysis and ground truthing, remotely sensed data are some applications that we see being very useful. We have bathymetry maps for all of our sanctuaries. Cordell Bank comes up from thousands of feet depth to about 120 feet, the shallowest sampling or observations you're going to do there. Flower Garden Banks is a sea mount that rises out of depths to about 60 feet, but goes down to about 800 feet where we want to do some research.

<u>Deep Water Corals</u>: Deep water coral is found in most of our sanctuaries and is a significant, highlighted research topic right now. Deep water monitoring provides us the data that shows the status, trends, and fluxes of resources in our program and allows us to make management decisions to change and influence those trends. Specific resources that this applies to are fish, corals and other invertebrates, and marine plants.

<u>Monitoring</u>: We are starting marine reserve monitoring at the Channel Islands National Marine Sanctuary, in partnership with the State of California. Our component is in the federal waters part, which is also “the deep water.” No-take reserves are not necessarily consistent across our program, but they will be used in the Channel Islands, starting next year. When we put in a no-take reserve a few of the recreational and commercial fishermen in the area are frustrated. It's important that we able to show that the reason for putting in these reserves is based on sound information. That requires understanding what happens to those communities of fish, coral and invertebrates in those reserves once those reserves are in place. Monitoring data can show the abundance and sizes of fish and those resources that previously were being extracted or are changing.

Deep water monitoring to support event responses and conducting rapid assessments of damage caused by anchor drags, or assessments of RUST (Resources and Under Sea Threats) targets are submerged wrecks, dump sites, and other interesting DOD things out there that we have to keep track of in our sanctuaries' boundaries are all potential activities for deep diving. Deep diving will be a useful application for getting down, studying, photo documentation, or collecting water quality samples around those targets. The Luckenbach off the coast of California was found to be leaking oil periodically that showed up on the coast of California, the Gulf of the Farallones and Monterey Bay beaches, as well as on otters and sea birds. Our understanding of what's coming off of RUST targets is important to how we manage and protect those resources. Concentrations of brine seeps in Flower Garden Banks National Sanctuary and the sink holes in the Thunder Bay area are interesting features that would require deep diving capabilities to study. Artificial reef contaminates need to be monitored over time from the artificial reefs that we put in place voluntarily or inherited once we designated a sanctuary.

I'd like to reiterate the importance of safety for divers. These waters are not the friendliest of places, maybe not as drastic as the Antarctic diving, but under Dave Dinsmore's NOAA Diving Program, we're in pretty good shape.

Cost is also important to us as a federally funded program, which in today's climate can fluctuate in its appropriations level. We've been asked to provide a Congressional briefing on how we apply science to management. Steve Gittings will present next week examples of science that directly supports our management and show how we use scientific information and the direct application and results of science to support our management activities. Much of that science is support with diving operations. We will show that the diving capability within NOAA and NURP Centers is important and supports directly what we're mandated to do.

I would like to thank Michael and the Smithsonian for hosting this event, and I look forward to building on the ideas we have discussed over the past two days.

J.Wilkins: What would be the top one or two immediate deep water targets that you'd like to go after if you were to prioritize and you had capability next year to go do it? What systems would you use to get it?

M.Tartt: Channel Islands monitoring is really important. That's a requirement that we're going to have to go through. The commercial lobby for recreational fishermen is important so us being able to demonstrate that what we've designed is going to be effective is equally important. The second one would be documentation of these submerged culture resources.

J.Wilkins: How would you characterize the actual work that you'd be pulling out of that from a monitoring standpoint? What is it that you need scientists at 300 feet to actually be looking for and doing and would you use surface-supplied diving, a sat system or CCRs?

M.Tartt: I'm probably not in the position right now to tell you which system since I’m not that familiar with all of them. I've been on a massive education curve over the last two days. We do assessment data, using transects, looking at the corals and invertebrates and roving diver techniques to collect fish census data. What we'll need to do is calculate species diversity, abundance and distribution of the target species that we're trying to protect in managing those deeper waters. It seems to me that tether diving in that situation might not be the most convenient, but saturation diving would be more relevant and use of rebreathers. Within NOAA we have a ways to go before that's a possibility.

J.Wilkins: Because I'm not a scientist, could you help me understand if you were trying to establish a baseline for those assessments, why would a continuous underwater camera monitoring system not help you figure out what's happening down there to get a baseline. Months later you could capture the same area with an ROV or a fixed remote system rather than a scientist in the water?

M.Tartt: It's an interesting question because obviously you want to try to minimize your exposure and risk to your employees. The value of having a scientific diver or someone knowledgeable of all species in the water and the ability to move around and observe on a more readily available basis adds a lot of ability to collect data. We just used some ROVs in the exploration of the Davidson sea mount, just off the coast of California. We're trying to expand the Monterey Bay Sanctuary. Those are about 2,000 to 4,000 feet and the field of view is very small. Your ability to actually follow and track fish and also to collect data in terms of abundance and size can be more restrictive. You can't do it with laser scales, but once you get in the water, clarity, movement of fish, stability, current, that data can be tougher to collect. The ability to be hands on is important in that respect.

Quenton Dokken, Texas A&M University, Corpus Christi

I appreciate being back up here today. What has struck me with great impact in this meeting are the advancements that have been made through the AAUS and NOAA and coming up to speed with the rest of the world relative to technology. It used to be interesting when we'd have NOAA divers on the boat with us and they were having to use dive tables and the rest of us were diving computers. They got a lot of topside time.

The purpose, why are we putting the scientists in the water? Why are we expending this energy worrying about the natural resources? I'll use the Gulf of Mexico and Caribbean as my reference points since that's where I primarily work.

The Gulf of Mexico, by any parameter that you want to measure, whether it's habitat quality, quantity, or fisheries resources, they are all on a downward trend despite all of our best management efforts. What we have done with our management efforts is reduce the steepness of that slope, but we have not brought it back to neutral or put it on an upward trend as of yet. Consequently, this is a time in the history of science that we really need to be putting more effort into scientific research and exploration, not less. Seeing NOAA lose a major part of its funding for NURP programs is of great concern.

Commercial exploitation, whether fisheries or hydrocarbons, has us moving into deeper waters with more intrusive methods. Non-source point impacts are extending to deeper habitats. Recently I had my staff take the census data from 1980 to 2000 for both the U.S. and Mexico and apply the average growth rates in the coastal counties in the Gulf of Mexico. By the year 2100 we could have a continuous metropolitan area from Cancun, Mexico all the way around the Gulf to Key West, Florida. If you think that our management struggles and challenges are great today, just imagine what our children and grandchildren are going to be dealing with.

With the start up of the space program we began to pull the scientists out of the sea and put them back into the laboratories. We now see a movement to get the scientists back in the sea. Certainly, they need to be there. As we look at the various diving technologies, one solution does not fit all projects or all people. If we look at these types of technologies going to the deep water, the more advanced the type, the more strenuous the technology that we have to deal with. Take somebody my age, mid-50s, who's been in a laboratory; you're not going to pull them out of the laboratory and convince them all of a sudden to take up diving and jump into the water. What we're really faced with today is persuading those students, the younger generations that are deciding whether to be a laboratory scientist or get in the field and see what's going on. How do we attract them into the programs. This is where academia, the university setting, comes in. I don't have the numbers, but I would guess that 80 to 90 percent of those who call themselves scientific divers are associated with universities. University systems do not maintain large diving systems, we look to NURP and NOAA and then we try to maintain a corps of divers within our systems.

We have personnel issues as we talk about moving into these deeper areas that range from 200 to 600 feet and are probably one of the least explored scientific areas within the oceans. We really don't understand why this is so, but it's just never been focused on. I know it's been difficult to get divers down prior to the last decade into those areas. Submersibles of various types have been too expensive to pay a lot of attention to that area. But to understand the ecosystem dynamics to achieve a sustainable management strategy, we have got to better understand this.

From the science community perspective, the level of funding is important, there's just no way we can get around that. The Navy paradigm has the federal coffers to work with, to whatever extent they can talk Congress out of dollars. Commercial diving serves the huge oil and gas industry relative to what we have to work with in the university and science system, a tiny blip on the funding scale. That does not lessen our responsibilities to society, to our professions, to the future generations to provide this scientific information. We struggle with that constantly. The Navy works with orders of $2.4 million, the commercial industry with several hundred thousand. Well, we can do it on $10,000 or $15,000, that's not an exaggeration. We don't have the same labor costs that the commercial sector has but do have this corps of students to work with.

Do we need to be developing all of these technologies, whether it's surface-supplied diving, bell bounce diving, rebreathers, trimix, or open-circuit? Absolutely. We have got to continue to develop them and encourage the new scientists coming in to apply these, not simply as a necessity, but also as something that they see themselves a very important part of. Scientific divers are typically scientists first and divers second. To get into these deeper and more advanced technologies, we've got to bring our focus on the diving up to the same level as we put on our statistical analysis, our observations, our instrumentation. That's what we're working at.

Again, Michael, thanks for having us here, this is great and we ought to do it at least once a year.

Rosemarie Petrecca, Rutgers University and Mid-Atlantic Bight NURP

Thank you, Michael, for inviting Joe Dobarro and me to attend this meeting. I am the technical and operations director for the Mid-Atlantic Bight National Undersea Research Center. In our center, we utilize and operate some of the latest technology from fiber optic cable observatories to autonomous vehicles. Our underwater cabled observatory, LEO-15, is in 50 feet of water.

Since 1998, we have logged hundreds of dives per year using surface-supplied diving because that has been the safest mode for us to use to achieve the scientific goals. The importance of LEO-15 is that it supplies our scientists with continuous 24 hours, 7 days a week worth of data, which is what they want. When one of the sensors is not working properly, guess who gets the phone call? What is really special about LEO-15 is that scientists are now able to get this continuous data in some of the worst sea conditions and storm events. Everyone is very excited when a hurricane comes close to the New Jersey shore and they don't have to be out there in 15-foot seas deploying their sensors over the side of a ship.

What also enables scientists that are funded through our research center is that LEO gives you a stationary platform of data collection. We also use autonomous vehicles from Remus to web gliders to get the spatial distance away from that stationary one center point of data collection. The scientists who are funded through our Center are really objective-driven by the Integrated Ocean Observing Systems. What they really want to do is be able to go further offshore, because the further you go offshore, the more questions you ask and the more interesting the whole science becomes.

What's the best way for scientists to do that? We suffer terribly from budget cuts every year. Our maximum funding for science projects is $40K per year and that's just for the science, not for the operations end of the project. A scientist wants to be able to get the greatest product for the dollar and so what's the best way of doing that for them? It would be not by putting divers in the water, but by deploying in situ sensors that are maintained and monitored by divers, by putting more buoy systems further offshore, because to lay a fiber optic cable out to the Continental Shelf is really cost prohibitive at this point.

When you think about what it is going to take to get a scientific diver out there, it's going to be a whole variety of means and modes, from in situ sensors to putting divers in the water. Depending upon the task what is going to be the best mode? Is it going to be surface-supplied diving, trimix or rebreathers? All this technology really needs to be developed to the point where it's safe for the diver and for the scientist who wants to be able to dive that deep.

M.Lang: Is there a future plan for the Rutgers-based NURP campus to conduct deeper water work with a LEO extension?

R.Petrecca: There's always lots of talk about a LEO extension and at this point, because of a lack of funding, if we go further offshore, it's going to be using a moored buoy system with sensors that will have telemetry via satellite, iridium satellite or free wave and by more frequent utilization of autonomous vehicles.

Adam G. Marsh, University of Delaware, Lewes.

The needs and interests of scientists for deep diving activities are going to be highly individualized. My perspective is just the one little narrow focus that really interests me or excites me about the kind of science that I do, which focuses on understanding how embryos and larvae of marine invertebrates are able to survive and develop in harsh marine environments, particularly in polar environments with limited nutrition, energy, and where metabolic efficiency is at a high premium. I study the molecular and biochemical adaptations that are necessary to ensure that early development is completed successfully. We know that in these environments there are large organizational shifts in how gene expression events are coordinated, how gene products interact, and different metabolic pathways that may be up-regulated or down-regulated to affect the overall energy balance of an embryo or larva as it develops into a juvenile.

We've heard how the continental slope or the 200 to 300-fsw habitat and environment is very different than in shallow habitats (0 to 200 fsw). Most scientific diving (and hence research) is conducted in less-than 60 fsw (Norton, 1994; Sayer and Barrington, 2005) and consequently there is a large amount of essentially 'unexplored' marine habitat between 100 and 300 fsw. These deeper water environments have very different ecological structures and unique species assemblages (Kendall, *et al.*, 2004; Rowden, *et al.*, 2004; Milessi, *et al.,* 2005; Stevens and Connolly, 2005). Deep dives into the 300 fsw realm very frequently provide for the discovery of new species (Pyle, 2000; Lechanteur and Griffiths, 2001; Rowden, *et al.,* 2004; Bouchon-Navaro, *et al.,* 2005; Milessi, *et al.,* 2005; Parrish, *et al.,* 2005). So we know that understanding and describing these deep-water environments is very important for our understanding of marine biodiversity. I would extend that biodiversity description to say that there's a lot of molecular and biochemical biodiversity that still exists within the organisms that are adapted in that habitat range that needs to be explored as well. The slope range between 200 to 400 fsw is an area in which you have a much lower input of food or available energy resources. Therefore, individual competition or individual species interactions become much more important and critical in structuring habitats and there is a higher premium on mechanisms of biochemical and metabolic efficiency for all organisms (at all life-stages) that inhabit these depths.

I've done some deep work in the DSV Alvin for about three years and it was always very frustrating to look out a porthole and see something that was right there and the only way to get to it was to nudge the pilot and say “hey, bring the arm out on the port side. Now what about collecting that clam there. No, no, that one right there.” After five minutes of positioning and getting the arm in place, coaxing the pilot with “yes, yes, a little closer, closer…” and then -- squish. “Oops. Well, how about trying to collect that one over there . . . ” Robotic arms are just not designed to perform the delicate collection tasks that many scientists require.

When I do fine-scale work with collecting embryos and larvae, this is really tiny, delicate stuff; it's certainly work that just cannot be done by an ROV. It really takes being in place and literally having your face in the bottom, in the substrate, in the organisms, looking around for egg cases or for larval stages that are being brooded on adults, and looking for adult organisms that might be gravid and ready to spawn. My work would require the ability to collect these samples, return them to a research platform, and be able to make measurements of gene expression rates and metabolic rates.

This 300-foot sea water level is important. There's been a lot of talk about walls, how important it is to go down on a vertical surface that clearly adds another 100 feet to one’s project scope. However, on most of our continental margins our slopes are not vertical. In general, an average slope angle exists at a 1% incline. Going from 200 feet to 300 feet, that 100-foot working depth increase gives us about 1500 feet of linear bottom depth to cover. A 100 fsw change doesn't sound like a lot, but in terms of the biological scope of area that it would open up for exploration for scientists to collect and study from, it really is a fifteen-fold increase in unit area.

It is also important to get below this 100 fsw level because any marine habitat above the 100 fsw level has been so heavily impacted by recreational divers. You have to go to fairly remote sites like Antarctica to find places that are relatively undisturbed. Particularly along our continental margins and slopes, getting down deeper gives you a refuge from those human impacts and would provide scientists with access to “natural” communities to study.

I'm also interested in doing a lot of work using *in situ* enclosures for embryological development by putting embryos back into the water column instead of trying to culture them in the lab during development. This has worked out fairly well in Antarctica because of the extreme clarity of the water and low epiphytic fouling community. In a deep water setting a lower epiphytic fouling rate would also make these enclosures potentially successful, but would require routine and constant monitoring, access, and manipulation. Thus, a very active diving program in the 200-300 fsw range would be necessary to conduct this kind of work.

Overall, deep diving capabilities for scientists would open up new marine habitats and areas for exploration, that would provide scientists like me with access to observations/samples/collections that would: 1) increase our estimates of marine biodiversity at the species level, 2) open new areas of research into molecular and biochemical diversity in these species, 3) represent biological communities with few human impacts and disturbances, and 4) potentially allow for more complex experimental equipment deployments given the low rates of epiphytic fouling.

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Anson H. Hines, Smithsonian Environmental Research Center

I've been involved in the Smithsonian diving community and its administration for a long time, and for the most part we've been involved in diving activities that are managed at the Diving Control Board level within the AAUS framework. The AAUS organization and standards with a maximum diving depth to 190 fsw have been helpful to us, resulting in both a productive and safe research diving system, and I'm grateful for that.

Generally, when you want to conduct research that requires deeper activities, it means using big ships, going a long ways offshore, potential danger, and we don't go there. However, when we began to think about some of the other perspectives that deeper diving technologies provide to us, there are immediate interests at the Smithsonian. We Smithsonian scientists are a curious lot, in more than one way. I'd like to give you a sense of some of the activities that the Smithsonian science community has been doing that provide opportunities of great interest to pursuing research in deeper waters. There is a big diversity of possibilities and interests when you talk to people in the Smithsonian, and I'll touch on a few of them and then spend a bit more time talking about our coastal field stations. I refer you to our website for additional information: **www.si.edu/marinescience.**

The National Museum of American History, Division of Transportation, is very interested in ships and ship wrecks. Some of our divers have spent quite a bit of time on ship wrecks, recovering them and studying them in places like the Great Lakes and Hawaii. Many other wrecks of great interest are deeper than 190 feet, and we certainly would gain a great deal of benefit by having access to deeper waters.

At the National Zoo there's an active research program on marine mammals, with particular interest in foraging ecology and diving physiology of sea otters to pinnipeds to whales and to manatees. Many of those organisms are routinely going to deep depths. These animals are generally big, and one can use telemetry, for example, to study their diving profiles. But if you want to know what's available to those organisms to feed on and exactly where they're doing that, it would be very useful to be able to sample the bottom and observe their foraging behavior at depth.

The National Museum of Natural History has a lot of interest in a wide range of science disciplines. They are interested in archaeology and anthropology of sites that are underwater, flooded to depths of hundreds of feet during rising sea levels over the past 10,000 years or so. Systematics and geological processes, particularly in marine systems, are also a primary focus at Natural History. Deep reefs are particularly important. We have participated in much research using submersibles and have highlighted some of those projects in IMAX films on the Galapagos and other sites. Use of submersibles has been helpful, but submersibles are expensive and not as accessible to the average scientist in the Institution, their collaborators, and students. Natural History curators provide systematics expertise for many taxonomic groups that certainly don't stop at 190 feet deep. Even algae in clear water often occur deeper than what we generally perceive of as the photic zone. This systematic research is providing a very valuable resource to the marine science community to understand and identify the diversity of organisms that comprise these crucial ecosystems.

The Smithsonian Marine Science Network (Lang and Hines, 2001; 2005) is composed of four long-term field stations that have been well-established for over 30 years and provide great opportunities for access to a range of marine environments from the temperate zone to the tropics. The Network includes the Smithsonian Environmental Research Center where I am, and we study large coastal landscape systems like the Chesapeake Bay. The Smithsonian Marine Station at Fort Pierce studies Gulf Stream organisms and the Indian River Lagoon, a 156-mile long shallow-water system along the east coast of Florida. The Smithsonian Marine Field Station at Carrie Bow Cay, off the coast of Belize, is studying the Meso-American Barrier Reef system. The Smithsonian

Tropical Research Institute is looking at the isthmus of Panama and has easy access with its array of facilities to two oceans.

The value of the Smithsonian Marine Science Network is in the conduct of long-term studies and access to field sites and logistical support, which makes it very easy to sustain multi-disciplinary research across these widely distributed, distant sites. You can board an airplane in this city and be working at any of those sites on the same day, which is phenomenal for sites that are fairly remote, not just Chesapeake Bay, but also Panama, Belize, or Florida. Our funding comes from a variety of sources and sustainable funding is a big issue these days, as you've heard many of us repeatedly state at this symposium, so cost effectiveness is important. We involve a lot of collaborations across many types of institutions at local, state, national and international level of government and industry. We're very interested in education and conservation, just like universities and the federal agencies. Importantly for these research diving programs, these permanent stations provide a safety and technical support system that's in place to support researchers in a cost-effective way.

The deepest point in the whole Chesapeake Bay is 192 feet. What's the big deal? Why would we need to use deeper diving technology? Actually, a lot of things come and go off the adjoining continental shelf as a part of the connected ecosystems. Most of the organisms that are estuarine and coastal have migratory stages. There are larvae and adults coming and going from much deeper water by moving vertically up and down on tidal cycles, and we'd like to understand how they can do that, where they are, and what they are doing, and not just when they're up near the surface. All the processes of material that's flowing out of the estuary, and the salt and other associated chemicals that are coming in, are coming ultimately on and off that linked continental shelf. The system is not only the conventional view of a 164,000 square mile watershed and the estuary, but the estuary and the coastal continental shelf system, which is deeper than 192 feet.

In addition, we have programs like the National Marine Invasive Species Research Program that is based at SERC. Our Marine Invasives Research Program is arguably the largest and most comprehensive such program in the United States. We have a network of sites along the continent surveying and analyzing the vectors and biodiversity associated with invasive species that are having enormous impacts in these systems. Most of those invasions are associated with bays and port systems, particularly focused on shipping activities that are in shallow water and do not necessarily require any deep diving technologies, but not all of them. There is an invasive tunicate that's covering the bottom, at 33 meters, but it's covering places like Georges Bank now and the ecological impact and the financial consequences of that invasive species are substantial. There's much interest now in sea mounts and deep reefs from conservation points of view and the impacts of fishing gear and certainly we're interested in those as well.

The Smithsonian Marine Station at Fort Pierce focuses on the long, thin coastal zone of the Indian River Lagoon that extends from above Cape Canaveral all the way down to Jupiter Inlet, pretty much the whole central east coast of Florida. It's a great site with access to many ecosystems and habitats that comprise the Indian River lagoon, other parts of the coastal zone, and the Florida Keys. A key habitat that has attracted a lot of attention is the deep *Oculina* reefs offshore that have suffered big impacts and are endangered. There is much interest now in trying to get access to them, not only through submersibles, but also through other diving technologies. We need to understand the fragile nature of these corals, which are long-lived and slow-growing, so that we can understand them as a habitat with many associated species, and the human impacts of trawl damage, sedimentation, and dredge-well dumping that is occurring on those fragile systems.

The Smithsonian Marine Field Station at Carrie Bow Cay in Belize is an idyllic setting on a three-quarter acre fragile island that provides a base of operations and access to the shallow-water coral systems, the sea grasses, and the mangroves associated with the Meso-American Barrier Reef. For decades, we've looked at it from the point of view of the reef crest and shallow habitats, but as divers, we've always wondered what lies offshore. Just a hundred meters away, not a ship ride away, from the limits of your Smithsonian scientific diving certification limit is much deeper water with lots of interesting biology and geology. Deep reefs are providing sources of propagules and diversity that are coming in and going off of these shallow-water systems. It's a continuum, and we very much would like to be able to sample those deeper habitats.

The Smithsonian Tropical Research Institute in Panama has a long history of marine research as well, focusing on shallow species, coral biology from spawning biology to evolution to genetics. Increasingly, deep species such as bryozoans and particularly fishes are research targets at STRI. Many of those research projects involve identification and the systematics of the organisms, but the basic biology is key to understanding and conservation of fragile tropical ecosystems. Many of these organisms are cryptic species that are coming from deeper water or only using deep-water habitats.

Diving has been a great boon to our research, of course, and when asked why we want to go deeper beyond this dangerous edge, I'm reminded of a story that I encountered about 30 years ago when I was working on kelp forest communities at Hopkins Marine Station in Pacific Grove. I went out one early morning on an optimal low tide in December with an intertidal biologist colleague of mine. He spent about a half an hour railing me about the time I was wasting as a scientist on all the logistics of scuba diving to 40 feet. I agreed that it took more effort than working at the surface and in the intertidal zone. At the lowest point of the tide on that foggy morning I reached down and pulled up this tiny little *Tegula* snail and he said this thing is so rare, it's great that we found it. I started laughing because there were thousands of them just 20 feet offshore that were accessible by any diver and we just thought of those as the most common organisms. It's all in your perspective about what's common, what's accessible, what you can study and the questions that you can ask. Access to greater depths will be more difficult, but it will allow additional important research too. We need to go beyond these shallow systems. They are literally the tip of the iceberg and much of what is inaccessible to us now is there waiting to be studied.

What are the priorities and which of these sites that we've been focusing on would we choose? Part of the answer is based on funding, but there are different strategies for this. If you're looking at the economic importance of an ecosystem, maybe Georges Bank is where we ought to be focusing our attention. If you're interested in the issue of conservation or impacts of humans, maybe the *Oculina* reefs, which are long-lived, very fragile, and have very slow recovery times is where we ought to be focusing attention. But if you're interested in trying to get at some of these basic questions, maybe we ought to simply look at what's logistically easy, rather than picking the hardest, most unfriendly system, to work in. Perhaps we should go to some idyllic place like Carrie Bow Cay, where just a few meters offshore you have access to 800 foot depths, a long history of databases and a diversity of people who can use that site. Perhaps a HydroLab approach would be the way to go. I'm not sure what the correct answer would be in the end, but those are the ways we at the Smithsonian Institution are looking at deep science these days.

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Phillip Lobel, Boston University

It's been really interesting to sit through this session and learn about the different diving systems. I've been familiar with surface-supplied for a while. If it had been applicable to the types of science I've done and am interested in, I would have used it. By way of explanation, I'd like to show a short video of recreational bubble divers walking on the bottom of Saipan Lagoon (video shows non-diving tourists using surface-supplied diving helmets to walk on the reef). I understand that surface-supplied diving is easy and safe. What we're hearing here is the noise factor of bubbles from their free-flow helmets.

I work on where and when fish spawn, what happens to their eggs and larvae, and recruitment processes. A great deal of my research involves underwater acoustics. When fish mate, they make noise. We developed a variety of techniques for tracking where and when fish are spawning, by first being in the water, swimming quietly up to the animals, recording those sounds and then applying a lot of existing technology that the Navy has for underwater acoustic tracking. It obviously has a lot of different applications for fisheries science and monitoring environmental impact. I have been studying fish acoustics through extensive use of rebreathers for a number of years.

When we review the kinds of technology available for us to go deep we also need to consider noise and disturbance. Every diving photographer (or bird watcher) knows that if you go down and create tons of commotion and noise (acoustic, but also physical vibration from bubbles), it disturbs things greatly. Putting divers in helmets on the bottom is great for construction and heavy work demand loads, but for observational science and surveys, but when you've got to be up close to a fish, surface-supplied diving is noisey and that causes some disruption, some disturbance. Clearly, we have different needs and different technologies. Besides noise and disturbance, we need mobility and dexterity to observe fish without disturbing them while underwater.

You know from following any of the recent work on particularly large fish spawning aggregations (such as groupers and snappers) in the Caribbean and elsewhere that many of these large aggregations are spawning in deep water. A symposium like this brings us deep divers out of the closet. There has always been an issue between diving regulations and our own capabilities and skills. We need to develop standards and techniques to put scientific divers in deep water.

One of the issues that we must addess in the academic system, like the military, is the process of attrition and elimination. Everybody can't do everything. Within scientific diving I would like to see a selection process where someone not only has to be scientifically capable but also technically savvy to dive with rebreathers or surface-supplied equipment. Unfortunately, a small, weak person can't easily deal with big, complicated rigs. It's a mistake to think that we can do that. As Diving Safety Officer of our program I get in the most trouble when I patiently sit down with someone and very nicely tell them they cannot dive deeper than 90 feet. I just don't think you've got the training, the experience, or the maturity that it takes. I see this as being one of the real problems; how we establish physical and psychological criteria for diver selection. Obviously, NASA must have huge amounts of experience in that regard.

Another aspect mentioned here was hybrid technology. Prior to doing deep dives I find it effective to launch a small ROV over the side of the boat, drop it down and scope out potential dive sites. I can then decide when I'm going to get in the water and what bottom time and gear I'll need to do the dive.

I see a potential collision happening with AAUS regulations and some of the themes we are discussing here. There has been discussion about what is scientific diving, in particular regarding instrument deployment, and what is commercial diving. Placing a big cement pile or a heavy item under water would be considered commercial diving, a scientist shouldn't do it. However, if you're going to go down and put in a little widget or a temperature logger, a scientist can do it. The problem is establishing the boundaries and realistic guidelines. Every speaker has talked about budgets. If restrictions come to science saying that we can't do the work that we are trained and confident in doing, but have to hire commercial divers to do it, that will kill science really fast. When we discuss commercial diving systems, we're using them to do science, but is this now going to be commercial diving? Are we going to get into a quagmire of regulations? Are we going to have to have commercial divers on site running our rigs or NOAA? The cost of these operations then goes up and for scientists like myself, who dive different parts of the world on fairly autonomous projects, that just becomes impossible.

The application of surface-supplied diving to deep water is a possibility in another aspect of work that I do, primarily with the military in underwater assessment and mapping of dumps and contaminants. I have spent a lot of time in the water looking at military dump sites and have worked with the chemical weapons program. From the news you may be aware of the "discovery" of a lot of underwater chemical weapons disposal locations in coastal waters around the United States and Hawaii. We're just now gearing up to consider what we are going to do and how we are going to do it. One of the first things I need to do is get in the water and start to look at these places to determine how we're going to do it. Clearly, surface-supplied diving is a good tool for this type of deeper diving. However, the issues that I have with how I look at fish (mobility, dexterity, and stealth) are the some of the same you want to consider when you're working around potentially unexploded munitions. You will not want to be stomping on the seafloor carrying things. You'll need to be able to control yourself and make as little of an acoustic or physical imprint as possible.

This has been a fantastic learning session for me. Thanks for inviting me to participate.

K.Huggins: Regarding the commercial/scientific issue, it's not about necessarily going out and hiring commercial divers. If you don't meet the scientific diving definition, you then have to follow the OSHA commercial diving regulations (not AAUS) as published. If you can do that in-house, then you don't have to go out and hire a commercial diver.

M.Lang: It would be inconceivable that we could run a waystation program without a Jack Baldelli, Gary Beyerstein, or Mike Gernhardt, people with extensive commercial diving expertise. I can’t foresee a conflict in contracting someone with those credentials to becoming part of the science team because of their expertise with the operations, tables, and equipment. The nature of the commercial and scientific activities are clearly delineated by the Department of Labor (OSHA) in the Code of Federal Regulations, along with the pertinent definitions.

D.Southerland: It appears that the diving systems that scientists will end up choosing will be functions of what science they need to get done, the funding they have available, and the acceptable risk of an unfavorable outcome(s), which includes not only not getting the science accomplished, but also morbidity and mortality to the people. There has not been much discussion about acceptable risk for whatever we do, with two exceptions. It was mentioned that scientists can abort a dive and the other that the fatality rate among rebreather divers was reported was approximately one half of a percent amongst those that are bought. As long as you're willing to state what your acceptable risks are, that can then save everybody a lot of time and determine what kind of rig to use and how much training you need to have.

J.Styron: Regarding the qualifications of the people that are going to be doing these dives, when you get to this level of diving it's not just taking somebody who’s nitrox certified, can breathe off a rig, and throwing them in. This is a totally different ballgame. Even if you're on the end of a hose at 300 feet, you're still at 300 feet with physiological and psychological considerations. There has to be a very stringent selection program for these divers with political correctness thrown out of the window. Just because a scientist wants to dive doesn't mean they can. You're going to shrink your acceptable scientist population down so much that you will really have very few that can physically and psychologically handle this type of diving. People using this scientific diving are scientists first, divers secondarily. Many we know go down, get focused on their work and everything else is irrelevant.. If they didn't have a buddy watching over them, they'd sit on the bottom until they ran out of air. At this advanced level of diving, you can't have people do that. They have to actually be better divers than they are scientists because a dead scientist isn't going to produce anything.

M.Lang: Except create a lot of paperwork for you.

J.Styron: True, if we don't list them on the dive log, we can say they were never there. It’s worth looking into training divers from different organizations that can make up a team. If you have scientist who passes all the qualifications, but that one person really isn't enough to do a whole mission, you have people you can draw on from other organizations to come in and team with them. From the projects we've been on, every member of the dive team doesn't need to be a scientist. Often, you just need to hold the end of a transect tape while doing the surveys. Constituting an advanced dive group gives you divers to call to make up a team.

M.Lang: That model works in particular situations, if you have a service-based facility such as the Aquarius program where you have permanent full-time staff that are specialists in each particular area and are available as resources. It’s perhaps more difficult in a university environment, or within our different research units here to pluck people out of their ongoing duties and responsibilities. Nonetheless, we would like to encourage that operational model.

J.Styron: Prior planning, perhaps at least a year out, gives you time to find people. When you get to this advanced diving level, people look more as the romantic end, want to do it to say they’ve done it and can find a science project to fit the bill. Proficiency needs to be key in this. Not all programs can have their own surface-supplied or technical diving system at their university. We'll train people right before their mission or they’ll come back within a month. We know they're not doing any trimix diving for proficiency from when they leave us until they come back. At this level, the divers need to consider this as life support and they have to realize they're ultimately responsible for their own safety. Somehow a proficiency system needs to be built in.

D.Dinsmore: I am concerned about the ready embracement of technology by some diving programs without validation of it. Just because a rebreather is for sale, doesn't mean it's safe. Just because a trimix dive computer is available for sale doesn't mean it's safe. That's why at NOAA we are taking a hard stance about adopting rebreathers and mixed gas dive computers. We're just not going to do it until we see that they've been validated and properly third-party tested.

P.Lobel: It's a great discussion, but often when we talk about these types of issues, we're thinking about our past experience, our existing scientists, and the way things are being done now. The other approach we can take now is writing the job description. We've got to get deeper. My primary job as Professor is bringing in new students and training them from the ground up to be scientists. At the same time we're now saying that to be the marine scientist who's going to go to the new frontier in deeper water, you've got to be a technical diver. Often when young undergraduates ask me about graduate school, I say go join the Army or the Navy, or do something for a couple of years, grow up, and come back. I work with many Navy divers who want to know what to do next. Could they come back to grad school? In a way we are starting to specify what the needs are for the future in terms of marine science and now we've got to start to define how are we going to build and train those scientists.

M.Lang: Very good point. If my friend Sylvia Earle were here she would perhaps make the observation that there are limits to wet diving and we might put scientists in a DeepRover or DeepWorker submersible.

M.Lang: For the next part of the workshop program we have invited two individuals to give us their synthetic perspective and own ideas about what they've heard presented, the data submitted, and discussions we've had thus far. This will, in effect, help lead us into a general discussion, which will then culminate this afternoon with findings and recommendations of this workshop that we can reach consensus on. For this purpose we've invited Lee Somers and Gary Beyerstein to share their remarks on advanced scientific diving.

Lee Somers, University of Michigan (ret.)

I wish to thank Michael Lang, Gene Smith, and the sponsors who made this workshop possible. I extend a special thank you to each of the speakers and workshop participants. All presentations were interesting and informative. I'm looking forward to reading the proceedings of this workshop.

I can view scientific diving to 300 fsw (91 msw) in a somewhat different perspective than many workshop participants. During my diving career, I was privileged to work in the fields of scientific, commercial, public safety, and recreational diving. In addition to diving with the open-circuit scuba commonly associated with scientific diving, I used surfaced-supplied masks and helmets, hot water suits, and closed-circuit mixed gas scuba. I would be remiss if I did not extend a special acknowledgement to two diving pioneers, workshop participants Bev Morgan and Dick Long. Their valuable contributions to diving technology are paramount.

Scientific Diving Today

To better acquaint participants with current scientific diving activity, I'd like to share three years (2002-04) of statistics from member organizations of the American Academy of Underwater Sciences (AAUS). Of more than 300,000 person-dives, 94 percent were made with open-circuit scuba, 1.2 percent with conventional surface-supplied equipment that included communication, and 0.3 percent with closed-circuit or semi-closed-circuit scuba. Dives beyond a depth of 190 fsw (58 msw) documented in AAUS statistics represent only 0.1 percent of the total scientific dives. Be aware that these numbers may not be truly representative of all scientific diving. There are scientists in governmental agencies and the academic community who are using systems other than open-circuit scuba (*i.e.,* semi-closed and closed circuit scuba) and making very deep dives. Most of these dives are not documented in AAUS statistics.

Today, we have the average scientific divers at 30 feet who are very comfortable with their scuba diving equipment and skill. Most of these scientists are not at all interested in developing and maintaining a higher level of proficiency or using other modes of diving. Science prevails! In fact, it's hard to even get some of them to recognize that a Diving Officer exists. Then, we have the better-than-average scientific divers. These are the ones who envision challenging underwater research missions and are interested in exploring better ways of accomplishing such missions.

Finally, we have the extreme scientific divers. These scientists are more or less equally interested in the technology to work underwater and the potential for scientific accomplishment. They are willing to commit to the rigors of extensive training and development of a very high level of proficiency in order to accomplish their scientific mission. Some of these scientific divers have extended their underwater research to depths well below 300 fsw (92 msw) using closed-circuit mixed gas scuba.

Extending the Depth of Scientific Diving

The question that we face today is, “How are select scientists going to dive to 300 feet in the future?” Modern diving technology has enabled human divers to work at extremely deep depths for many years. Today, we, as the participants of this workshop, are being asked to recommend a path for future deep diving programs and systems that will enable scientists to perform productive research at depths to 300 fsw (92 msw) and, ultimately, deeper. Be mindful that we are not speaking of military or commercial divers who already have systems and procedures in place. We are not speaking of recreational divers who are free to operate independent of government agency- or academic institution-imposed regulations. We must consider diving equipment, procedures, and techniques that will be best suited for a particular scientific mission and for the scientists who elect to accomplish that mission. All available diving systems must be considered.

Cost is always a factor. Equipment for diving to deep depths is expensive. However, for those who really want to do it simple and cheap, I know two young women who can do it. Meaghan Heaney-Grier and Tanya Streeter can breath-hold dive to 300 feet, pick up a sample, make a quick observation and come back to the surface. They're really quite capable.

Atmospheric pressure diving systems (*i.e.,* JIM, WASP, Newtsuit) have already proven their value to the underwater scientist. Many scientists suggest that such diving systems are cost prohibitive. As previously stated, some scientists have already turned to closed-circuit mixed gas scuba. This equipment is within the financial means of some scientists, and dives in excess of 300 fsw (92 msw) can be conducted from a small boat. Other scientists have adopted the open-circuit scuba techniques used by recreational-technical divers. Self-contained divers encumbered with many scuba cylinders and multiple regulators have survived dives to depths exceeding 500 fsw (137 msw).

New innovations in compact remotely-operated vehicles (ROV) can provide scientists with an affordable means of observation and sample collection in selected environments. Surface-supplied diving equipment and techniques have considerable merit for underwater research. The scientific community is in a position to learn from the experiences of others who have already worked at deep depths. The hardware and procedures for deep diving have been developed and tested. Now, this equipment and these procedures must be refined to serve the scientific community. To make a dive to

300 feet for 20 minutes, I can choose a very large diving system or a very small system. I've done it with both and there are considerable differences.

Dr. Egstrom revealed that early scientific divers were diving fairly deep (*e.g.,* Bob Dill's work in Scripps Canyon). In more recent years most scientific divers appear to favor shallower water. Is this movement to shallower water attributable to the recreational instruction influence, concern about liability factors, or the nature of the scientific mission? As we move back to deeper water we must be vigilant of both internal and external influences. Do we follow the path currently taken by the extreme scientific divers, or do we seek to explore what some may consider as more favorable options.

At present, it appears that most discussion is directed toward short duration dives. However, as mission requirements call for extended duration dives and decompression becomes longer and more complex, saturation diving techniques become more desirable. Below 300 fsw (92 msw) saturation diving will be necessary. Refinement of lightweight, highly mobile saturation systems should be a serious consideration for the future and may be one of the best ways to extend scientific diving down to 600 feet. However, below 300 fsw (92 msw) atmospheric pressure diving systems and remotely operated vehicles may be a more viable option for many scientific studies.

Protection from the Environment

Diving to 300 fsw (92 msw) requires adequate thermal protection. Hot water can be supplied to a diver via the umbilical. This factor alone increases the appeal of surface-supplied diving. However, a dependable means of protecting the diver from injury or illness associated with environmental pollutants must also be considered. Totally encased surface-supplied divers have successfully worked in extremely polluted water. On the other hand, some authorities feel there are significant reasons to revisit equipment requirements and procedures for protecting divers in some environments.

Decompression

I didn't give much thought to decompression protocol before attending this workshop. Now, I have many questions. For example, have the models used in programming computers for trimix diving and multi-gas decompression been satisfactorily validated? Have the numerous computer-based decompression programs been satisfactorily validated? It appears that the scientific diving community must identify a validated decompression protocol for diving in the range of 200 to 300 fsw (61 to 92 msw).

Chamber Issues

The scientific diving community at-large has very limited experience with on-site hyperbaric chambers. Furthermore, our community has virtually no experience with surface decompression in a deck chamber breathing oxygen. This is a common practice for commercial and military divers who have very specific requirements that dictate the presence of a chamber on-site for deep diving operations. On the other hand, there are no such requirements in AAUS diving standards. And, recreational-technical divers dive in the range of 200 to 400 fsw (61 to 122 msw) or deeper and complete lengthy, multi-gas in-water decompression with no thought given to having a chamber an on-site.

I will cite my personal experience as an example of problems scientific divers can face when attempting to provide on-site chamber support. In 1970, I purchased a standard double-lock off-shore chamber for the University of Michigan. I was committed to providing university divers the level of protection afforded military and commercial divers. Unfortunately, the vessels provided for scientific diving operations lacked sufficient deck space and lifting capacity to facilitate the chamber and support equipment. A vessel capable of adequately supporting diving operations was never acquired. In fact, over the years diving operations were transferred to smaller and smaller vessels. The chamber sat on shore (on a trailer) or in my laboratory.

With a few exceptions, on-site chamber support for scientific diving operations has been virtually nonexistent even though simple but adequate chambers are affordable. This is a reality! Fortunately, scientific divers have developed conservative approaches to deeper diving and decompression as a means of reducing risk. In spite of common practices in the recreational and scientific diving communities today, it seems reasonable that all possible avenues of providing a rapid treatment capability for an injured diver must be explored. Hopefully, improvements in first aid and treatment protocols and future development of smaller, lighter weight, and more affordable chamber systems can ultimately provide divers with a greater degree of protection.

Fitness to Dive

From the medical standpoint, the current AAUS and NOAA medical standards appear to be satisfactory for diver screening. However, I personally feel that physical fitness criteria should also be considered. A reasonable level of fitness and strength is essential to manage the equipment, environmental stress, and mental stress associated with deep diving. Keep in mind that the requirement for long decompression time makes deep diving overhead environment diving. As in cave diving, direct escape to the surface is not a viable option. A physically fit diver is often more capable of managing mental stress than an unfit diver.

Training for deep diving must also address the topics of stress recognition, reduction, and management. It is very likely that a diver's well-being in overhead environment diving is 60% related to mental (emotional) fitness compared to 40% physical fitness. Program developers are encouraged to review training requirements for cave divers, where stress-related training is essential. Personally, I feel that my early cave diving experience significantly influenced my mental attitude and emotional fitness for deep diving.

Risk Assessment

Risk assessment is essential! There are risks associated with any dive, regardless of diving mode and depth. However, as depth increases, the risk of decompression sickness also increases. What incidence if DSC can we accept? An important factor in planning any dive is risk-benefit assessment. Do the benefits or scientific knowledge to be derived from the dive justify the risks that might be associated with making the dive? An objective pre-dive risk assessment can often identify potential problems that can be prevented. The same applies to developing a diving program. Keep in mind that failure is not an option. As a community of divers, we must understand what level of risk we are willing to accept to achieve scientific advancement. Risk assessment applies to both individuals and institutions or programs.

Closed-Circuit Scuba

As previously discussed, closed-circuit scuba currently appears to be the mode of choice for deep scientific dives. Are there safety issues associated with this mode of diving? Absolutely! However, there are safety issues involved with any mode of deep diving. Scientific divers are bred as open-circuit scuba divers. It is logical that they would turn to closed-circuit scuba for diving to deeper depths. Most are not familiar with alternative diving modes. We must remember that any mode of diving has advantages and limitations. Satisfactory training and operational criteria must be clearly defined for any mode of diving. Safety issues must be identified, discussed openly, and well understood.

Surface-Supplied Diving

We gathered at this workshop to discuss extending the depth range of the scientific diver. We would be remiss if we did not discuss the advantages and limitations of a proven and reliable technology applied in commercial and military diving: surface-supplied diving.

My perspective on the subject may be more open than that of some scientific divers, because the first 200 dives in my life as a teenager were made using a shallow-water mask supplied by a compressor on the surface. Then I discovered the freedom of scuba and have been fortunate enough to be exposed to many diving systems during my career.

Surface-supplied diving is the mode of choice for most commercial and military diving. It has earned this status because it meets the mission requirements for specific underwater tasks. Surface-supplied equipment is dependable and well-suited for the working diver. Personally, I wholeheartedly support the use of surface-supplied diving for scientific research. In fact, in the late 1960's Bob Anderson and I were faced with tasks such as recovering large quantities of surficial sediment from the bottom of Green Bay for geochemical research and conducting biological research in Grand Traverse Bay. At that time the two of us were responsible of all University of Michigan research diving in the Great Lakes. We were working at depths to 100 ffw (30 mfw) in 40º F (4º C) water on these projects. We concluded that scuba had many shortcomings for this type of work and, subsequently, acquired a surface-supplied diving system that included hot water suits. Our mission capabilities were greatly extended, the quality of data acquisition improved, and higher standards of safety were maintained. Operational efficiency was significantly improved.

Unfortunately, commercial and military surface-supplied diving systems require a relatively large and stable platform as well as heavy lifting capability. The U.S. Navy's Fly Away Diving System weighs about 38,000 lbs (17,237 kg). Equipment weight and volume can make use of such diving systems prohibitive in a research setting. For example, our system had to be transported in a Suburban and carried on to the research vessel by hand. In subsequent years, we successfully conducted surface-supplied diving from 16 ft to 100 ft (5 m to 30 m) vessels. Some dives were to depths exceeding 200 ffw (61 mfw). We even conducted surface-supplied dives from a Suburban parked on the ice in the middle of Grand Traverse Bay. University of Michigan divers successfully used scuba, tethered scuba, and surface-supplied diving to accomplish a variety of underwater research missions.

Mr. Dinsmore's presentation reflecting on NOAA's surface-supplied diving experiences brought a sharp note of reality to this workshop. Surface-supplied diving can be challenging. There are platform- and environment-imposed limitations. There are human limitations. Does the scientific community have the appropriate vessels to serve as surface-supplied platforms? Can surface-supplied research diving operations be staged in rough seas or strong currents, and on vertical walls? Will the average scientist have the necessary physical strength to manage an umbilical? Can our community develop satisfactory training programs to transform a free-swimming scuba-oriented diver into an umbilical diver? By what criteria will divers be selected for training and missions? Who will train these divers? How long will it take to train a diver to go to 300 fsw (91 msw) using surface-supplied diving equipment?

Training the Surface-Supplied Diver

Allow me to reflect on some of these questions raised above. Scuba diving scientists can be trained as surface-supplied divers provided that the course is of sufficient duration to allow for a proper orientation to equipment and procedures and includes a significant number of open-water training dives. With sufficient practice, most scuba divers can learn to manage an umbilical; however, not in all sea conditions. For example, I have trained 95 lb (42 kg) young women to comfortably dive using surface-supplied equipment, but I would not deploy them in high seas or strong current.

The scientific diving community must develop satisfactory operational and training standards for surface-supplied diving. Training must be scientific mission oriented, not commercial or military. Certification criteria must be standardized. Currently, we do not have a surface-supplied diving training program in the scientific community that is designed to universally train scientific divers, to 30 feet or to 300 feet. In addition, to my knowledge, there are no "certified" surface-supplied diving instructors in the scientific community. There are excellent individuals with military or commercial backgrounds who may be well-qualified to teach surface-supplied diving. The scientific community should develop criteria by which to identify and certify these individuals.

In my opinion, one or more surface-supplied diver training facilities or mobile training teams should be developed. For example, some NOAA-supported facilities (or institutions) may have both personnel and equipment to provide such training. The mobile training concept was not discussed. However, years ago I trained several small groups of scientific and public safety to conduct shallow-water surface-supplied diving operations. I traveled to training locations with a complete surface-supplied diving system to provide theory, confined water, and open water training. In addition, I advised some groups on equipment purchases and advanced training options. Possibly, a qualified person or organization could acquire funding to better develop and test the concept.

After reflecting on the views expressed at the workshop and my experience with scientific divers, I envision a four-phase training program starting with tethered scuba diving and advancing to shallow-water air/nitrox surface-supplied diving. The last two phases would progressively expose trainees to deep air and trimix decompression diving with qualifying dives ultimately to 300 fsw (92 msw). Trainees would be trained to fill the roles of diver, tender, standby diver, rack operator, and supervisor. This cannot be a four-day training program. Ideally, training phases would be spread over a period of months with opportunity for divers to gain personal experience between phases.

Obviously, organizations serious about developing surface-supplied diving capability will have to purchase “starter” shallow water diving systems that could be expanded into deep diving systems as experience and needs dictate. This is economically feasible. Phase training allows the diver to gain confidence and skill progressively. The diver and support team must be comfortable with the equipment at 30 fsw (10 msw) before ultimately advancing to 300 fsw (92 msw). Both divers and their institutions will have to make a commitment. A diver cannot be trained and then not given an opportunity to participate in surface-supplied diving activities for the next 18 months. There must be equipment and a proficiency maintenance program at their institution.

In addition to training divers, the scientific community must also develop guidelines for selecting proper support vessels and for training vessel crews to properly support diving operations (*e.g.,* mooring).

Why Make the Transition to Surface-Supplied Diving?

When all is said and done, the human products of these new training programs must be subjected to profiling and discrimination. Diving program managers and supervisors must be allowed to designate divers who they feel can meet the demands of the scientific mission and environmental conditions. A certification card cannot be a ticket to dive on any mission; it is only document to introduce a diver to the supervisor.

Scientific divers have been free swimmers and independent thinkers. Now, they will have to meet the supervisor! Their dive will be controlled from the surface. For those who have spent years trying to circumvent the institutional diving officer (you DO’s know what I mean), there will be a rude awaking.

The true advantage of deep surface-supplied diving is that the supervisor and surface personnel can relieve the diver of many of the physical and mental tasks commonly associated with deep scuba diving. Task loading can induce a high level of diver stress. When tasks such as dive timing, gas management, gas switching, decompression stop depth/time management, etc., can be managed by someone on the surface the diver can operate more efficiently and at less personal risk.

A good supervisor can "read" the diver's breathing pattern and voice to gain insight into the diver's physical and mental status. I learned the true significance of managing a dive/diver from the surface from Dr. Joe McInnis by observing him at a dive control station. Two divers were deployed in a bell to 250 feet on a B-52 crash site in Lake Michigan. One diver remained in the bell to tend the umbilical while the other deployed to identify meaningful wreckage and rig it for lifting. The diver transmitted video images to U.S. Air Force personnel on the ship in order to identify wreckage to be retrieved. The diver's breathing rate and strained voice suggested over-exertion, possibly to a dangerous level. Attempting to complete the laborious task before his time limit expired, the diver did not heed Joe's order to stop and ventilate. In a calm voice Joe requested the diver to immediately return to the bell and asked the tender to haul him in. The dive team got the message and obeyed. By "reading the diver" and controlling the dive from the surface, a possibly bad outcome was thwarted.

The scientific diving community will have to establish guidelines for developing a surface-supplied diving system(s). Systems such as the Navy's Fly Away Diving System are excellent, but a bit overwhelming for the average scientific diving program. Initially, air/nitrox diving systems will have to be compact, portable and expandable. Keep in mind that many diving operations will be conducted form small boats. Costs must be reasonable, not prohibitive.

There are many diving system components currently available. The scientific diving community, with guidance from manufacturers or other diving authorities, will have to develop a system from these components that is user friendly for the scientific mission.

Scientific scuba divers should make the transition to surface-supplied diving for specific missions and environments. In time, they will find that advantages far outweigh any disadvantages. Deep research missions can be accomplished with greater efficiency with less risk to the diver.

The Hybrid System

The term, hybrid system, is used to define a diving system that embraces both scuba and surface-supplied technology. A system of this nature was developed by Innerspace Systems, a Gulf Coast commercial diving company, in the late 1960's and successfully used for selected commercial diving tasks in the early 1970's. The primary gas supply system is a closed-circuit scuba on the diver. Consequently, a very low volume of gas is used for any given dive. Consumables cost only a few dollars per dive. The makes the system very attractive. Gas is re-circulated though a helmet or mask. The diver is also supported from the surface by a small umbilical. The umbilical can provide an emergency gas supply from the surface to a demand regulator on the helmet or mask, voice communication, system monitoring, depth monitoring and hot water for a suit (as needed). Modern technology should be capable of developing monitoring electronics that can feed information such as PO_2, cylinder gas pressures, carbon dioxide level, and depth to a surface console display. Properly designed and proven through rigorous testing, this system could be the missing link: a cost-effective, compact, portable diving system to more satisfactorily support a scientific diver at 300 fsw (92 msw).

Deep Mixed-Gas Diving: Immediate Future

For the time being, a small number of scientists will use closed-circuit mixed gas scuba. The equipment is relatively affordable and cost of consumables such as gases and absorbents is low. Deep dives can be staged from small vessels. This type of diving appears to be economically and logistically feasible. Keep in mind that this type of diving is for a few committed scientists who are willing to accept responsibility for training and equipment maintenance. They must also accept the limitation of the equipment as well as risks inherent to deep scuba diving. Hopefully, innovative individuals will find ways to reduce risk and improve diver efficiency. System redundancy, conservative decompression protocol, deployment of underwater refuges (way-stations) at work sites, etc., might be considered. Training, operational, and maintenances protocols must be improved. However, I do not believe that deploying free-swimming scuba divers at 300 fsw (92 msw) to conduct research is the ultimate path to follow.

A larger number of scientists will no doubt follow the lead of the recreational-technical diving community and deploy to 300 fsw (92 msw) using open-circuit scuba. These individuals must be mindful of the limitations of this system for a working scientific diver. In addition to making scientific observations and collecting specimens, the diver must assume responsibility for gas management, dive timing, and buddy awareness. In some cases this multi-tasking can induce stress. Diverting attention from such tasks as gas management to complete a research task can lead to dire consequences. There are many other reasons why open-circuit scuba would not be my personal choice for deep underwater research.

As compact remotely-operated vehicles become more refined and affordable, some scientists will further explore the vehicles' research potential. These vehicles will be used to complement or replace diver deployment for some research tasks currently performed by divers.

The Not So Distant Future

A few responsible individuals and organizations will further explore the concept of reversing more that 50 years of scientific diver evolution and experiment with surface-supplied diving. I suggest that the benefits of surface-supplied diving will ultimately overshadow perceived limitation in accomplishing certain underwater research missions. Researchers will have to understand that there will be diving platform- and environmental- induced limitations. However, the full potential of surface-supplied diving will not be realized until appropriate diving systems are defined, training programs are in place, and appropriate diving platforms identified and refined. Ultimately, some of these organizations will work at 300 fsw (92 msw) with great success.

Idealism

Presently, government funds are used to support vessels and an underwater habitat for conducting scientific research. If the scientific community is going to truly embrace the concept of placing surface-supplied diving scientists at 300 fsw (92 msw) and deeper, we need a vessel specifically designed for and dedicated to this mission. Ideally, this vessel would be designed for work site stability and maintaining position. It would be equipped with a mini-saturation diving system that could be used for both short-duration bell- supported non-saturation dives and for saturation dives. In addition, the vessel would be equipped with two atmospheric pressure diving suits and a state-of-the-art remotely operated vehicle. I respectfully submit that as the Aquarius underwater habitat nears the end of its useful life, a surface-based deep saturation diving system should be a priority consideration. A vessel and diving system of this nature operated by a professional scientific diver support team could well serve the goals of the Ocean Action Plan.

For now, if the scientific diving community is going to extend the operational diving depth, let’s do it right! The program cannot be put in place overnight. Furthermore, it will require a coordinated commitment from individual scientists, scientific diving organizations, government research agencies, and funding agencies.

Gary Beyerstein, SubSea International (ret.) and Commercial Diving Consultant

Lee Somers is a very tough act to follow. I must admit that I didn't hear a single thing that he said that I disagreed with. In fact, I felt like getting up several times and cheering. Before summarizing points that I noticed during this conference, I would like to add my thanks to Gene and Michael for inviting me here and for the opportunity to talk to you. I'd also like to pay my tribute to two people who have made commercial diving possible the way I know it, who have laid the foundation for what we do: Dick Long, who made it possible for us to dive eight hours in 40 degree water out of a bell, and Bev Morgan, who provided the basic standard for the gear we wear. In the earlier days, most of my diving was with a Superlite 17 and a KMB-10 band mask. I never liked the 17 because my head was small, but there's a 27 now and I'd use that if I could. I loved the band mask!

The focus of this conference was predominantly surface-supplied diving. Glen Egstrom made a statement that said we must be willing to change our minds to eliminate our prejudices. I firmly believe that if you're going to go to 300 feet, surface-supplied diving is the safest way to do it, other than perhaps in a saturation system. It has become apparent to me during the course of this conference that that's going to be difficult to achieve for the scientific diving community. There are many problems to overcome and as Lee Somers pointed out, you have somebody here who's already done it and abandoned it. That's a great tragedy because you were almost all the way there. Perhaps the few problems with your methodology could have been solved.

The major problem with the scientific diver, as Michael has stated to me, is that there's no academic recognition for the skill that he has to acquire to do his science. Somehow or other the scientific diver is supposed to magically qualify, get down there, and do his science. A scuba diver can get scientific diving certification and dive to work at 100 feet; 300 feet is a world of difference on mixed gas. It's not something that everyone can do and your community is going to have to recognize that.

People can be trained to use the equipment and can be trained to do whatever task is required that is ancillary to the equipment that goes with your scientific mission. However, the equipment and the mode of diving has to be matched to your mission. It's obvious from some scientists that surface diving is not a good fit for their mission. Whether that can be changed through techniques that can be adopted to make it easier is possible and needs to be explored. Some of you are doing it anyway (deep diving), probably outside the umbrella of your organization, you're sneaking it in. Perhaps that's an unfair statement, but it's the impression I get. You're getting away with it so you must be doing something right.

From the papers presented here and my own personal biases, it doesn't appear that decompression computers are where they need to be yet. It doesn't appear that we have tables that will suit your need yet as far as even surface diving is concerned in situations where you want to be able to go up a wall and do multi-depth, multi-gas profiles. There are no dive recorders out there that will record gas switches, even though you can buy a nice Citizen watch that will record and download to a computer a complete dive profile, including a surface exposure and a chamber exposure. These are points that will have to be addressed if we want to get what we need to go where we want to go. Where we want to go is to have a good database that incorporates all the experience.

There are pockets of expertise here that aren't talking to each other or sharing data from the world of recreational divers, commercial divers, and military divers. That information is not being collected, analyzed and there's no good science being done with it. I don't know how we assimilate that information, but certainly amongst the scientific community you should be able to set up a mechanism for doing that as part of your procedures and be able to address exactly what information you need.

We have the techniques to do good modeling. It may be that the only people who can do it (develop new tables) are the military because of their ability to do manned testing, but they have to have a mission in order to be able to accomplish that. It's a theme that's being recurring over the course of this whole process, almost like you can't get there from here. I don't care to be negative about it, because obviously you're doing it and you have to get there from here. The question is how. I don't have answers other than to echo Lee Somers. There's a good way to do it and a bad way to do it and as Michael has stated, you can't afford fatalities. Your risk tolerance is very low. Just as Innerspace was shut down by one fatality, your whole diving program could be shut down by the wrong information and the wrong publicity.

You're on the hairy edge right now. Those of you diving deep with closed-circuit rebreathers are using tables and computers that aren't validated. Divers respond that they've logged 300 dives and so the table must be alright. That's the level of experience you're getting right now. You have 300 or 600 dives with that piece of equipment in your own little pocket of expertise and you're saying that's good. As a safety manager for 20 years for major diving companies, it's not okay. You don't really know how good that is until you have several thousand dives logged. The incident rate for these rebreathers is not 0.5 percent, it's probably considerably higher if you take into account all of the technical divers doing this (and the level of under reporting). They are really pushing back the frontier and the envelope in a way that is not for everybody, certainly not for the average scientific diver. Unless we can find a way to make that safer, it will continue to not be a method for everybody.

CCRs may be the wave of the future, but they have to be controlled. There has to be some good science involved in order for it to be acceptable and provide a level of expertise in your training and a level of safety in your deployment to make it a reasonable option. For the next few years it will continue to be on the fringe. As much as I'd like to have a rebreather myself and dive to 300 or 400 feet for a few minutes to look at a shipwreck, I was bent, paralyzed from the waist down in New Zealand and it's a frightening experience. It happened to me on the way up in a chamber from a 110 foot dive using modified U.S. Navy sur-D-0_2 tables. I was bent in the North Sea on a dive that I could have made with dual 50s. I experienced the chokes and a spinal hit from a dive that was well within No-D limits. There was nothing unusual about the dive procedure, it just happened. One factor was cold, the other perhaps a hot shower after the dive, who knows? Without a chamber on site, I might not be here talking to you today. The kind of dives some of you are doing to those depths without a chamber on site is unconscionable to me. You should not be allowed to do it, period. Now maybe you won't like to hear that, but that is the opinion I'm sticking with.

You've got to find a way to do it. If it can't be a double-lock deck decompression chamber, a Hyperlite is not going to suffice to treat a diver from a deep gas bend. The chamber capability must be deeper than 60 feet. One option to explore is the Italian company GSI that had a 60-bar chamber that you could pack up and carry with you. They hadn't tested it with helium, so for the application I was considering, it wasn't applicable. The problem with these off-the-shelf products is that they're not approved by PVHO. Whether the scientific community needs to have a chamber that's PVHO certified, I don't know.

I will make a comparison from the early days of diving when we had hyperbaric welding done by divers from saturation. We don't do much of that any more because we have smart flanges and mechanical means. Do we make divers welders or turn welders into divers? We found it much easier to make a welder into a diver than the other way around, similar to the scientist and diver scenario.

Mike Gernhardt is an astronaut and former deep sea diver. He's also a scientist with Ph.D. in biomechanical sciences who's made significant contributions to the diving world. Only two astronauts are selected out of 20,000 candidates. Now that's selection! We go to space because of a military objective and a science need. Scientists go to space, but not before submitting to a severe selection process. Now you want to put a scientist at 300 feet. I suggest you think about the selection process because it has to be more than just experience diving to 100 feet. You now have a science project to 300 feet because there's more stuff down there than you've been able to reach.

We have the technology to make better tables and the technology to put you there safely, but it's expensive on a surface diving application. We have perhaps the technology to do it in a semi-safe way with a rebreather, but I don't think that's what your program can stand or is ready for yet. You're not in the position where you can reliably make hundreds and hundreds of dives over a period of years and take a chance on having somebody die needlessly, especially when there's no chamber there to treat them. If you have a bend and a chamber with the right training to report and treat it, it's as though the incident never happened. As Jean Pierre remarked, you have that golden window where the lack of perfusion causes the tissue to stop functioning, but there are enough alternate routes of perfusion for the central nervous system tissue that it doesn't die yet. By treating the diver immediately and thoroughly at the right depth, tissue perfusion is restored and you go on about your business. Without on site treatment capability, you will have permanent residual symptoms, crippled divers, or fatalities. This would precipitate lawsuits in the commercial world and negative publicity for your science programs.

The Coast Guard has a situation where they're responsible in many cases for environmental pollution and hazmat emergencies. They have strike teams that are trained to deal with that. When the situation arises, the Atlantic or Gulf Coast strike team responds. It might be an option for you to have selected, multi-disciplinary scientists who can be temporarily removed from academia to receive the training to be able to respond to these deep missions year-round. It may not be ideally what you want, but a way to get there for now. This would provide your core group to spread your training around, help apply it to other people, and expand your program. The Navy is probably your only hope for saturation and maybe even for mixed-gas diving right now. They have the capability, the facilities, and are willing to cost share if you can team up with them. Perhaps you can find other ways to build from out of your separate funding pocket, *i.e.,* one area where you have a focus and can define the mission to be able to carry out advanced scientific diving in the immediate, short-term future.

Again, thank you very much for your kind attention.

C. <u>General Discussion Session</u>

M.Lang: Lee and Gary, thank you again very much for your perspectives.

L. Somers: There is probably a place in the interim for a technical support team that is specially developed to support the scientific community in their effort and also have scientific divers that are specifically trained. That could be either be an in-house group or a specialized group from NOAA.

M.Lang: Dave Dinsmore may already wish he had stayed at home.

G. Egstrom As a way of looking at the last two summary presentations, I'm reminded of a quote from Poul Anderson who made the observation that he had never encountered a problem, however complicated, which, when viewed in the proper perspective, didn't become more complicated. It seems to me that's what has been happening. We need to recognize the problem and not let it defeat us. If we stop being progressive, then it's all going to grind to a halt. I just don't believe we can let that happen. We can only make diving as safe as possible, we can't make it safer. That may be trite, but often our intellectual goals and perception are such that we think we can make it ultimately safe. We cannot and therefore have to accept some level of calculated risk. 300 feet is a number, not a place, but a goal. 300 feet as a training objective where you're progressively going to stage down to some capability at that depth is certainly doable even if we look at records and determine that's really extreme. Record setting is by and large taking extraordinary levels of risk to push the envelope. We recognize that there's a bell-shaped curve associated with it and if we come back from the extreme position, we find a large body of knowledge and technology that will permit us to do just about anything that we reasonably wish to do. When we get ourselves into a position where we are arbitrarily fencing ourselves out of progress, we're making somewhat of a mistake.

D.Dinsmore: Sometimes the scientific diving community, of which I consider us a part, is driven by our financial situation. Doug Kesling and I have debated for years the use of technical diving and the need for a chamber on site. They now have one by the way. Before they did, I would ask if he thought it was the right thing to do and he would say of course it is. Then why don't you have it? We can't afford it and therefore we do without. That seems to me perhaps what's driving some of the scientific activities. It may not be the best way, but we've got this much money and we're going to do what we can with it.

M.Lang: I don't disagree with you to an extent, but don't forget that our mission is research and if we load up our boat with AEDs, oxygen kits, first aid kits, spare regulators, tender(s), DMT and chamber for regular diving, not much remains to do the research and that defeats our entire purpose. It's not as straight-forward as it's perceived to be because often we mitigate that risk of not having a chamber on site by diving fairly conservative profiles. Recall the progress we've made as a community since 1988. We've looked in-depth at dive computers, ascent rates have now been halved from 60 feet per minute to 30 feet per minute and we require safety stops. We've examined polar diving and repetitive diving, reverse profiles, and nitrox, all in an effort to make diving more efficient and mitigate our risk. It is true that the availability of a chamber on site was the number one issue we had with being included under commercial diving regulations. We could not afford it then and certainly cannot afford it now at the sites we need to work. Our research funding pie is finite and by slicing off ever larger sections for safety equipment and chambers that you can otherwise mitigate to a degree by diving conservatively, you end up with crumbs. I would put forth the notion that the degree of conservatism in our 190 foot operating window on compressed air scuba is reflected in our incident statistics of the past thirty years. We dive in some of the most remote sites on the planet, not just as a matter of distance, but also as a function of time to a recompression chamber and we mitigate that risk successfully.

P.Lobel: With all the exciting opportunity that's been laid before us is what's next after this workshop? Within our community funding is key. The first page you wrote to introduce this workshop really laid out the need to go deep and that's great as an individual scientist. I can show it to my administration and say this is why I'm diving deep because that's where the new frontier of science is. How do we get the funding? NSF will not likely issue a request for proposals stating a need asking who can put together a program. As individual scientists we're going to package up our own science and technology and say we're going to go forth and do it. Or, because of the infrastructure, the training, and the lack of experience we have in doing this, we've got to have some science training dives that clearly falls within the realm of the NOAA and NURP programs. We shouldn't just leave this workshop with the idea that these technologies are out there. There should there be a concerted community effort to say we need to set up a trial program. I love the idea of Carrie Bow Cay as a place to work from, it gets rid of the cold factor and provides good discovery opportunities. But do we get together as a group? This would be a fun group to dive with and certainly the people to learn from. Our level of comfort, if we're going to be there to work at these depths, would result in us having had exposure to the best, brightest and most skillful.

M.Lang: The real reason this workshop had to take place here is not just because of our social events, but because it is a similar process to what happened with the blue water oceanographers in submersibles in the early 1980s. The National Science Foundation did not fund the Bruce Robison's of the world because that technology was considered an elevator ride then. Exploration per se was not a fundamental mission or funding priority for the NSF. Over time, it took the blue-water oceanographic community's results and peer-reviewed publications to be able to document the efficiency and productivity of these very expensive systems. UNOLS is the University National Oceanographic Laboratory System, funded by NSF that operates the nation's academic research vessel fleet. They are very savvy as a community at coalescing behind common goals. UNOLS has standing committees such as the Deep Science Submergence Committee, Research Vessel Operators Committee, etc. That is one model to consider if we want to dive deep as a community, coalesce the deep diving scientists. Some of our interests will drive the process. If Rose Petrecca has no interest in 300-foot dives, she's won't be diving deep with you. In order to open our diving window and get this moving, we must have these workshop proceedings in hand with discussions of the advantages, disadvantages, selection process of science divers, training required, and which technology will work in various situations. The NSF Biological Oceanography Program will more likely entertain proposals containing deep diving methods that have been substantiated and will provide science results.

G.Smith: Several participants mentioned the magic 300 fsw and others have said that it is a worthwhile goal. It was picked partly because we had scientific pressure and partly because we thought in 2003 that 300 fsw was achievable. Crossing over that barrier of approximately 10 atmospheres would be considered an achievement. We want equipment to go to a minimum of 300 feet, that's why for surface-supplied diving or sur-D-0_2 we want a chamber that's capable of going back to depth. For bell diving we want that chamber capable of operating at 300 feet. If someone has a lightweight helmet good to 250 fsw, we'd like to know that too, because we're going below 190 fsw in stages and if it can only go to 250 fsw, fine. Realizing that our goal is 300 fsw, maybe you jump to something shallower first. Rose Petrecca talked about this international observing system or the GEOS (Global Earth Observing System) that has money. Admiral Lautenbacher from NOAA is our key point in America, the leader of that GEOS system. Scientists bend with the themes. You can bend your biology or geology to match the current GEOS theme and observatories are a big thing right now. If we have observatories, scientists want to observe in the deeper depths, which is where we get into that combination. These may be simple diving tasks. If a platform is placed down at 300 fsw and you have to take your readings from it, these could be very short, well-controlled dives and they may be easy. Design the mission and then work up the diving and qualifications to the profile. That's a key element emphasized today, trying to tie all that together. The next item we're getting into is partly common sense and partly rules. If a diver has made 400 dives, I'd say that person is probably doing safe diving and could continue to do that. Another individual may walk in using the same equipment and not be successful. We're trying to design a program that we can operate in a step-by-step fashion and make it available to those scientists who can pass through all the gates and are willing to invest the time, energy, and money.

K.Kohanowich: I liked your UNOLS comments, that's intriguing. Regarding NURP, as far as I know our only real on-paper mandate is from the Outer Continental Shelves Act. Is says the Department of Commerce will provide support for research on how to make diving safer for the nation. That has trickled down to the various chains of command to NURP. Of course, the NOAA Dive Program has overall responsibility of safety for divers who are NOAA employees. We don't have the responsibility for all of the safety and the procedures for all of you. Regarding the budget climate, everybody knows what's happening at NURP. We're vulnerable to shifts and Congressional direction. What we're faced with now is looking at the priorities and triage, what to focus on, where we can get the most bang for the buck and make the biggest contribution to the community under our budget constraints. What we were looking for and the workshop participants are working on really well is coming up with some of those ideas and suggestions, recommendations that we can take a look at and see how we can fit into our overall strategy.

M.Lang: I want to further your comments one step with something I've advocated for years that the American Academy of Underwater Sciences do. I say this as a two-time AAUS president in 1987 and 1991-1993. The main item currently preoccupying the AAUS Board is the day-to-day business management. They can't really sit down and write the proposals, or engage in development activities. I mentioned UNOLS because they really are adept at this and ships are big money. They cost a lot of money to build and operate, and there is an economic incentive for the university research vessel operator to get it together. UNOLS is exceptional, a community-based organization that acquires its operational funds directly from the National Science Foundation. They are very good and lobby through a thematic approach. Because of the congruence of the diving programs and the research vessel operators, the AAUS should take advantage of this model. These are the same institutions to a large degree. There are 19 RVOC operating institutions and about 90 AAUS programs. All RVOC institutions also have AAUS programs, reflecting a similar community of scientists who should band together. If this happens, a product similar to what Martin Sayer described, a National Center for Scientific Diving, could emerge. Once the infrastructure is set up, the community can focus on these larger projects, such as establishing a national facility for deep diving, buying equipment, hiring the experts to come in and train a group of diving officers. It all appears to flow from there and I would encourage the group to continue that evolution.

D.Kesling: We should come away from this workshop with a mandate that we can take back to administrators and show in black and white the need, the nuts and bolts for surface-supplied diving to 300 feet. We know we can do that with the right money and infrastructure to support it. Perhaps the MUST (Manned Undersea Technology) Program should be resurrected, declaring that this is what this community has identified and proceed to the national level, Congress. If we're going to be successful in our biology and ocean exploration we need this capability and it needs to be funded. The NURP program really needs to take the lead in getting that attention in order for this to be supported.

M.Lang: Even more so as a community-based effort, the involvement of the scientists is crucial. The researchers need to agree and press the science need and if the initiative goes forth from a community standpoint versus going back individually to their own universities, then UNCW may allocate the money instead of NSF or some larger funding body that would be willing to support such an initiative.

M.Gernhardt: There's a national need, if not a requirement, to put marine scientists under water, be it 300 feet or greater. It's clear to me that properly controlled surface-supplied diving is the safest method to do that. It's also clear that some of the science you do is not compatible with those methods, but I suspect that a lot, if not the majority, of the science could be adapted with proper surface-supplied methods to result in an effective system. The research grant levels don't seem to be consistent with individual organizations doing this diving and therefore it needs a phased approach, a national program that possibly starts out using existing assets, such as the NURP facility in the Keys. Before you dive into this with both feet and try to get a huge amount of funding, you need to start getting scientists working with surface-supplied gear, understand how hoses and science go together. That would build up an infrastructure, provide a training ground. Looking forward, there are opportunities to work with the Navy or the commercial contractors to have a surface gas set up that would either be portable or on a vessel, on a long-term call out basis, operating analogous to the Aquarius habitat as a national capability. Phasing it in over time with the right team of people will avoid a misstep along the way, which will kill this thing and you can't afford that.

D.Long: Having been around when many breakthrough procedures were developed, I would suggest we try to keep it as simple as we possibly can because you're having divers go someplace they've never been before. That approach usually has the highest degree of success in the early days and can be refined as we go along. Proceed in stages and don't try to get down to 300 feet if you've only been diving to 150 feet for a long time. Be careful when you write your regulations, because fences work both ways. Regulations are often used as a method of trying to make it safer when in reality, all it does is show you where to point fingers. Most of the advancements that are going to come to you in the future are from outlaws like me, people who are breaking the rules and not doing it the way it used to be done. I remember a time when I was asked to give a briefing to a diving organization in Britain by Shell Oil. They wanted to take these civil engineering divers and make them into offshore oil divers. We said we're going to take your big copper pot away and give you this band mask. Off with the big heavy weights for something small. Throw out the canvas suit because this new suit, rather than keeping the cold water out, is going to pump warm water in. This one fellow got up, walked over and put his arm around my shoulder and said “you're a nice young man.” Are you going to take my helmet away? I said yes. You're going to take my weights away? Yes. Are you going to take my suit away? Yes. You're going to pump water in on me, right? I said yes sir. He replied, son, I don't think you're big enough. As you move forward, you need to understand that regardless of where you are in the forefront of science, there are many scientists who have lived for years just like that individual has. Some of us right here, including myself, are rooted in our technology, but there are other technologies and approaches coming around the corner. We need to make sure that we keep an open mind at all times and listen to those outlaws. You may never know, but they might have a better way to do it, even though they wears earrings and have long hair.

P.Ruden: In Navy diving we have what we call extreme exposure. Once this workshop information is collated you're going to be able to draw a line and say we want to employ all these methods and what we know we can do is on this side of that line. The items on the other side we have questions about and operational risk management assessment, the importance to your job, will guide you and help prioritize. You may need the Navy to help develop a table or the commercial community for equipment. You need to get a straw man out of that before we leave.

M.Ward: In the commercial and military worlds, when a diver gets seriously injured, many questions are asked and everything comes under scrutiny. Especially in the commercial world when you lose a diver, there is litigation, keep that in mind. We're discussing 300 foot diving at extreme limits. Lawyers will get hold of that after a scientist dies and compare scientific diving to procedures the military and commercial guys use to mitigate those risks. They’ll say you knew what that diving entailed as far as commercial and military diving standards, yet you decided to do it anyway. Look at those risks carefully or they'll be in a position to shut everything down.

M.Lang: Absolutely, and I think nobody will argue that point. Nonetheless, I want to go on record stating that each diving community has its own standards of practice. Each community is characterized differently, not only in the severity of their profiles, the nature of the underwater activity, their mission, and operating standards, but also in how they manage the risk for their procedures. Under no circumstances would the science community accept being held to the standard of the commercial, military, technical, recreational, or public safety diving communities as reference for our standard of care. The scientific diving standard has evolved since 1951 at Scripps Institution of Oceanography to become what we've known since 1980 as the AAUS standards. Should University X decide to operate science diving programs well outside of the envelope of the rest of the science diving community, that becomes a significant issue. Obviously they would be imprudent by not following the standard of practice of this particular community and be exposed to significant liability.

M.Ward: Regarding standards, not to say that it can't be done, but many open-circuit trimix divers dive to 400 feet. There is no published testing that's ever been done for that. The reality is the Navy doesn't test to those depths for those types of dives because they don't have a need for it. I doubt that you'll find any of these manufacturers publicly endorsing the use of their scuba regulator on trimix down to 400 feet, regardless of some outrageous advertisements we've seen in the past. The bottom line is that there are no performance standards on any of this equipment currently available in the United States. That needs to be addressed before you go too far.

P.Lobel: One fundamental difference between commercial, military, and scientific diving is that we don't dive or train our people in less than ideal conditions. The data is not worth our life. When we dive deep, I pick the best conditions, I want it easy. The value of the observatory was not having to be out there in rough water, which is absolutely true. When it starts getting rough, my gear is knocking around and my camera is going to break. I'm going home, it's not worth it. If gear is not working properly, the data is not worth getting in the water for.

M.Lang: Scientific divers have the right and responsibility to abort a dive or choose not to dive without fear of recrimination or reprisal if the conditions are not good, the equipment doesn't work properly, they don't feel right, or they are exposed to conditions beyond their level of training and expertise. They are not paid to be divers, they are paid to be scientists. If one day they can dive no more for medical reasons or by choice, they are not in jeopardy of losing their academic appointments or salary, although they may opt to embark on a study of desert rats. The following statement encapsulates the scientific diving approach to risk management (adapted from material by Dick Vann, Duke University).

- The ultimate responsibility for safety rests with the individual scientific diver.
- Safety is the judgment of acceptability of risk. Risk is a compound measure of probability and severity of harm to human health. There are degrees of risk, therefore, degrees of safety.
- Estimating risk is a scientific event (an objective and probabilistic pursuit).
- Accepting risk is a political activity (a personal or social judgment).
- Nothing is absolutely free of risk.

5. General Discussion Session

M.Lang: We have approximately two hours left to decide what we would like, as a group, the workshop message to be. We should continue on with the discussion, and then formulate findings and any potential recommendations we would like to pass on.

K.Kohanowich: As a federal agency, NOAA can't lobby Congress. We are resource limited and there are really two ways to get money for NURP. One is with the Presidential budget for NOAA, and the other, of course, is the Congressional side. We're focused on the Presidential budget and what we have to do is defend any new initiatives against everything else that NOAA research and the rest of NOAA does. In order for us to best bring these proposals up to NOAA research and to Admiral Lautenbacher for additional funding for initiatives to help support what science wants to do, we're best served by your input to the community. We'll be looking at this report when we consider our budget requests.

A.Brubakk: I'm a little concerned about the direction that this discussion takes because I've been responsible for medical problems in a large diving company for many years. The point is that, if you want to go to 300 feet using commercial diving systems, that's an extremely safe operation. There are hardly any serious, and very few minor, problems at all with that kind of diving. There are thousands of dives performed every day, at least from the experience I have from the North Sea, but it is an expensive way of doing it. You are discussing many ways to say how can we make this cheap and keep a risk level that we're used to in scientific diving, namely zero problems. I'm very doubtful if that is possible. If you are going to try the simpler way of doing it, you may have to accept a higher risk than you have in commercial diving, and I don't know if that is acceptable to you.

M.Lang: I'd ask you to qualify the nature of the commercial dive to 300 fsw, because what we would likely do is a 300-foot dive for ten or fifteen minutes on the bottom, immediately multi-level up, which is probably not comparable to the commercial square-wave extreme time, workload, and decompression stress profile.

A.Brubakk: I fully accept that. But still I feel that the discussion we've had these last two days indicates that there still are a number of problems that have to be solved in order to demonstrate the safety of that approach.

M.Lang: Even by transferring the currently available commercial diving equipment and supervisory experience to this type of program? What needs to be validated?

A.Brubakk: We have a lot of commercial experience and know how to set up a system like this to make it safe as far as we can apart from blow-ups or some crazy accidents. My comment was rather to say that, in trying to find the cheapest way of doing it, you have to be very careful that you are not increasing the risk to an unacceptable level.

M.Lang: I accept your point. The responsibilities of our positions dictate that we be sensitive to the risk issues and thus cannot authorize science diving operations we feel exceed our acceptable levels of risk.

J.Godfrey: We have a different job as scientists and we have already been doing dives in this depth range. I'm just not seeing that our risk levels from those diving exposures have been very high so far. In fact, if you go back through some of the scientific diving material covered, the risk during those dives is actually very low, because we have training programs, diving safety officers and standards that we adhere to. Comparing the incident rates from the commercial or recreational industry doesn't really apply to what we're doing. We have the programs in place already and have the capability to make any of these modes safe within their limitations. The risk numbers are apples and oranges yet these are all viable modes and probably will all continue to be used in scientific diving.

W.Gerth: In response to the last comment, yes, scientific diving does have a very safe record associated with it. But how many of those dives are to depths deeper than 250 feet? I would say, not that many. So when you talk about apples and oranges, let's make sure we compare apples to apples. Commercial divers do go to those depths in great numbers with a lot of safety. I don't think you can make that claim yet about scientific diving.

M.Lang: I fully agree with you. And if we were to take our data on 250-foot dives today and try to get an exemption from OSHA, the experience base would not be there, okay? At the time of the exemption in 1982, our experience base was to 190-foot on compressed air scuba.

W.Gerth: I think that what Alf is driving at is, for example, you have said that you do a lot of your scientific diving without on-site chambers. Great. What you've done, right there, is accept a higher risk than a commercial diving operation would accept.

M.Lang: We have mitigated the risk of not having a chamber on-site by having far more benign, less stressful, types of exposures than commercial diving and that needs to be mentioned in this context of our experience base to date.

W.Gerth: Yes, except that 300 feet is not a benign exposure.

K.Huggins: The two points of contention that this discussion boils down to are chamber on site and training. If we looked at incorporating what the commercial diving does with a chamber on site, there would be no argument on the operations side, and we'd just have to look at training.

D.Long: I want to support those two points. Also, as Lee Somers pointed out, putting three additional horizontal transect points on a wall may be a difficult thing to do. Only on a vertical wall are you going to be able to do scientific work on the way up. If you are on a flat bottom, you can't do that. Some scientists may need to be able to move distances over the bottom of as much as half a mile, not a couple of hundred feet.

M.Lang: My experience in the science community is that the scientists and/or the project will determine the need and methodology. Most scientific divers will know exactly how they need to collect their data from the number of repetitive samples required by their experimental design. Much of the sampling protocols and depths will be driven by the science need. We need more options to work at these depths and are examining surface-supplied diving besides the available saturation, rebreathers, and open-circuit options. This option should not be eliminated because it won't work for some projects. There are many science projects where this method will actually work. We're trying to put on record the commercial, and the somewhat more limited military, experience with surface-supplied mixed gas and consider how we can create an action plan with that for science.

M.Gernhardt: I would like to again reiterate the phased approach. The first part of any of this is to start under controlled circumstances to understand how hoses and marine science work together, acknowledging that in some cases they won't. There will be other applications where you can come up with operational methods to still get the same product, but in a different way. As a community, we need to explore those differences and understand those limitations. Another fundamental question we have to ask ourselves is, are we trying to go forward with a diving method that would be applicable broadly across the whole community like a scuba tank that works for 50 different science programs? Or, are we looking at this as a national capability, like an Aquarius habitat, where select peer-reviewed research comes and uses this capability. In that regard, the issues about the cost can be diminished a little bit if you have one central capability versus trying to have everybody with a surface gas one.

M.Lang: Yes, there is NURP and the national federation for science diving, the AAUS. We should make it clear that it be considered part of their responsibility and the science diving community's expectation, programmatically and individually on a project basis.

D.Dinsmore: We are going to introduce a tethered scuba and a lightweight surface-supplied diving capability into the NOAA ranks and build that into our standard three-week working diver course. We have got to start somewhere. By training these NOAA people in these alternative techniques, once they get out in the field, they can determine that where there was once only scuba, an application for tethered scuba or surface-supplied diving may be appropriate. Maybe that's one way to start, following Michael's approach about training them and then seeing how they can apply the technology.

M.Lang: That is a very good operational point. One can stock a dive locker with two dozen rebreathers, the 'build and see if the scientists will come' approach. It may work, but if you have two dozen scientists knocking on your door saying you are my Diving Officer and we need to do this with rebreathers, you'll need to figure out how to provide that research support. The science needs to drive the methodology, not the other way around.

C.Cooper: I think there is still some confusion about NOAA in general. You've got the NURP Program and the NOAA Diving Program, where Dave deals with NOAA scientists. We also have all the AAUS members. UNC Wilmington is a NURP Center and also an AAUS organizational member program. Regarding a central location for mixed gas surface-supplied diving to 300 feet, all the different AAUS organizations are not going to want to set up a dive locker for mixed gas. There has to be a starting point somewhere. I'm a little confused as to how that would work so that we don't go in different directions even if we do agree to accept these commercial standards for mixed gas diving. Is Smithsonian going to go at it on their own? Is Delaware going to go do it? Or are they going to come to us and say, we'd like to dive under ice at 300 feet, would you train us?

M.Lang: The first line of a proposal cover sheet is going to have the name of the Principal Investigator, so it's got to be science driven. We'll need researchers who require the technology because of the science need, that's the very first step. Until that happens, we can prepare for it by training diving officers and scientific divers. The real use that results from this type of methodology is going to come from the science. If UNCW receives proposals every year requesting this type of diving, this capability will need to be developed and those researchers drawn in as the nucleus of users.

P.Lobel: I want to reinforce what Michael is saying. Listening to this discussion is exciting because I see a technology that I wasn't familiar with. Once I define a scientific problem, if I am convinced that it is really state of the art science and competitive, I don't think I would have a problem finding funding for this. I had no problem getting dollars to buy two rebreathers, it is driven by the science. There is discussion about national facilities, but it is hard to get beyond exploration and look-see, that's the first part. How do you get down there? How do you define the problem? How do you establish the hypotheses? We always have that problem of a phased approach. Part of the phased approach is certainly where the NURP Programs and others are getting technology, getting people comfortable, getting workshops like this together to ratify what the community sees as viable methods. But then, ultimately, as Michael constantly reiterates, someone has got to establish the scientific hypothesis and need that is driven by peer-reviewed science. It often becomes a chicken and egg argument, because how do you get down there to define what you can do scientifically if you haven't been there before? That's the conundrum that we are in.

M.Gernhardt: Some of you guys do a lot of diving and are great divers but to do science and stick you on a hose, you would probably not do very well. If you just went to Craig and said go do that science and he didn't understand your science, he would probably go down there and tear off the sponge or whatever else with that hose. You have to have a team effort to really understand what your science objectives and the operational methods are. We're all critical people, and I think we can come up with tailored techniques that fit each individual research area. There will be some projects it doesn't work on, but that's the whole phased program. Start out slow, understand how to work together, and then bite off the gas diving part of that later once you have proven that surface-supplied diving is actually viable. You're not going down there just to plant a flag at 300 feet, you are trying to do science and we need to make sure these methods don't compromise the science.

B.Morgan: You should consider re-titleing the 300 feet limit. What you are talking about here is helium diving. Now, I'd say mixed gas, but I don't want to confuse it with nitrox. But at some point, you've got to use helium for a reason and at that depth is where the big change takes place. As soon as you get helium in your blood, it's a real fast gas going in and out. You can't go to the surface (at 200 feet breathing five minutes of helium and going to the surface, you are dead.) That's a big difference from air diving to 250 feet where you are a little narc'd out, but, you are breathing a slow gas. By saying 300 foot, you are putting it forward as that being the goal. You are also putting forward that being the maximum depth. You might not want to limit yourself to 300 feet. You might want to re-think and re-title the whole thing to call it helium mixed gas diving starting at wherever you are comfortable, 240 feet, 200 feet? Where can you think clear?

M.Lang: That is a similar comment that Glen Egstrom made earlier. Gene Smith pointed out that 300 feet is an intermediate step, because he was talking about 650 foot depths.

G.Smith: Bev has a good idea because we all know that if you can convince a customer to pay for helium, they get a lot better job out of you at 130 feet on heliox than they do on air. It costs a little more money, but they get a better job. Switching to helium is the difference. We're not going to get to 300 feet and have sensible scientists on the bottom unless we do that. It is worth considering. Another aspect the 300 foot came from is proposal pressure. A scientist preparing a proposal has to say, I want to go to these specific areas and study these specific subjects. There's always a depth component and that gives them a guideline, but that can be worked out. Switching to heliox is a big point we ought to make.

B.Morgan: You're going to have an easier selling job saying 240 or 200 rather than 300 feet.

M.Gernhardt: You don't want to limit that, either. Glen was warning to not fence ourselves in too closely. There's a way to say it where you can get everything you want without locking into that.

G.Smith: Yes, and we would accept 100 meters.

Q.Dokken: That is a good point. Actually, I can't think of any justification to start putting arbitrary boundaries up front, because it does get codified into the regulations. Two years from now we'll find ourselves coming back and trying to make the argument okay, we've done that, let's go to the next level. Right now I don't know that anybody is expecting us to arbitrarily set boundaries. I think advanced deep diving beyond 200 feet, whatever we want to call it, leaves that window open.

M.Gernhardt: Set the lower limit, not the higher.

M.Lang: By the same token, I wouldn't want someone restricting us to use heliox at 130 feet since we've been diving with compressed air to 190 feet.

Q.Dokken: I haven't heard anybody say put those types of limitations on it.

D.Dinsmore: There is a dilemma for the NURP Centers. The NURP Center is a national asset. Any civilian scientist can apply to use that facility by writing proposals. If the score is high, our tax dollars pay for that. NURP has to solicit proposals. They've got to say to the community, we can support you on these activities to 300 feet. Before they are willing to say that, they've got to be able to back it up. That's their dilemma. Before they can announce it, they have got to have a technology to support the work at 300 feet.

J.Styron: I'd like to clarify what our UNCW program does.. The AAUS compressed air scuba limit is 190 feet. Now we're saying the next step is 300. But we're already doing dives between 190 and 300 feet on mixed gas, open circuit right now. This is not a dark area where nobody is going but are waiting to do it. This is part of the multi-disciplinary approach of marine archeology, biology, geology. Granted we're not doing truly long bottom times like we could out of saturation or some of the other methods, but it is a good starting point. Now the scientists we have gotten down there can say I do need to do this long transect, or if we had a sat system beside this wreck, I could map this out in a week as opposed to three or four years of coming down for a week at a time. To many of the commercial and military folks present open-circuit trimix appears to be one dive away from being dead. Originally, when the military and commercial divers first started out, they were all on the edge. You didn't have the numbers to back up what you were doing, and kept tweaking procedures, which was your assumed risk period. Now this is ours. We decide we're not going to have a chamber on site because we have one within an hour or two. We've got to put our individual prejudices aside for the greater good of where we are going to be. You have great surface-supplied diving and sat systems. This needs to progress in steps. Unfortunately, money drives a lot of this until we can get cooperative support between the different agencies and communities. For the record, we already are at 300 feet operating to our scientific level, not to the commercial or military level.

M.Gernhardt: That is great, because if you have an experience base, then you can bring the surface techniques in and understand the differences. You might have to change your method. Instead of doing 100-foot transects, you maybe do two 50-foot transects. But that's the right environment to develop those methods.

J.Styron: That's what a lot of our scientists have seen. Many have done the shallower work on nitrox where you've got an hour at a site. Now you are at 250 feet and you have 20 minutes maximum. We are shortening our transects by half. We may just do two short ones instead of one really long one. Or, you may come to sites that have heavy current at those depths. You have to modify your marine archaeology practices to take into account your shorter bottom times. The researchers we have worked with have had no problem modifying their traditional practices to work deep. We have hammered in that you don't have unlimited bottom time and an extra five minutes is going to cost 30 minutes decompression hang time. It takes a learning curve but we haven't had problems. We've already got the first step in this process going now.

D.Southerland: I wasn't really prepared to talk about rebreathers or open circuit. We don't have much surface-supplied HeO_2 diving done in the Navy. From 1998 to 2002, we had 95,000 reported dives on rebreathers, of which 80,000 were on oxygen rebreathers, really shallow dives. So it's only about 15,000 or so.

M.Lang: At 300-foot depths?

D.Southerland: Well, that was just the information from an old PowerPoint presentation. If I had a different computer and it had all the other data on there, I could tell you a little bit more. But that's it. So I mean there is some experience out there. But the focus for this meeting, I thought, was on surface-supplied diving. So I would think that the other modalities, such as rebreathers, open circuit, whatever, warrant further consideration. That is really beyond the scope of this meeting other than just to say these things do exist and should be, as any researcher would say, further research is warranted in this area.

M.Lang: The overarching theme of this workshop was to look at a 300-foot scientific diving capability. As I've said several times already, we could have spent two days talking about rebreathers, would have been no further along on them, and not have had the opportunity to discuss surface-supplied mixed gas diving. We've heard review papers of the status of rebreathers by Karl Shreeves and Drew Richardson, the AAUS rebreather standard by Bill Dent, saturation diving by Craig Cooper and several open-circuit trimix reviews. However, we needed to take the opportunity to look at some other methods besides rebreathers that would possible work for us.

D.Southerland: Surface-supplied diving for science is a tool in a tool kit that may or not be used. If you're asking me if these scientific divers needed to go in the next two weeks, I don't know what the rules and regulations are. A commercial system would probably be available to them and they could operate under certain standards, assuming they got funding for the project. Are we looking at short term and long term? Are you looking at trying to come up with a quick, short-term fix or solution, and then a long term one?

M.Lang: We support a phased approach and want to see if we can phase surface-supplied diving in. Evaluate if this works for a science project as one additional option, a tool to use to 300 feet besides open-circuit trimix or rebreathers. As you've heard from the science presentations here, there are some long term needs. For Smithsonian alone, we've been on site for 32 years in Belize, Florida, and Panama. I can envision these coral reef monitoring sessions going on for the next 30 years. It should be a long-term objective.

W.Gerth: I want to comment on a point Jay Styron attempted to make about how the technical diving, or scientific divers who are using rebreathers out there, now are phasing in the use of such gear in the same way that the Navy or commercial operations have done in the past with other sorts of gear. The U.S. Navy, at least in my experience, has not introduced any sort of gear by testing it in the field. Any piece of gear that we propose to have used by Navy divers is first run through a very exhaustive unmanned test program, and then run in manned testing in the experimental diving unit, during which time we fully characterize how that rig behaves. We don't just give it to the divers out of the box from what the manufacturer tells us it should do and see if it works for them. We first do an awful lot of testing. And in that process, the rebreather rigs, by and large, fail. We have some pretty stringent criteria for them to succeed, for them to be passed on to open water testing, and then finally approved for Navy use certification. We can't use our fleet divers, as I have heard scientific divers and technical divers are by other people, being used as their living laboratory. We don't do that.

M.Lang: Well, some of us government programs don't do that, either. I ask Dave and Gene to please comment on the status of rebreather evaluation within NOAA.

D.Dinsmore: When we started looking into closed-circuit rebreathers, we found that they had received very little scrutiny or third party testing. We funded NEDU to test two rigs, the CisLunar Mark 5 and the Buddy Inspiration. NEDU tested the

CisLunar (manned and unmanned), and the Buddy Inspiration (unmanned only because of safety concerns over the location of the battery in the breathing loop).

G.Smith: In 2003, Dave realized there were no standards for CCRs. There was nothing you could reference to determine if a product met acceptable performance requirements. Together, we facilitated the CCR standard that was circulated for review to well over 100 people outside of the two technical committees that helped write it.

M.Lang: Would that be the standard not a single manufacturer could meet?

G.Smith: At this point, no one has met it yet. The PRISM was already tested by NEDU and found faulty by Dave and others because of their quality control program, which hopefully now they have under control. As soon as the Inspiration gets back to NEDU and is tested with its new battery box, then it should pass. The NOAA standard also parallels the EU standard. The only real difference between the two is that they only require test diving to 10 fsw and we require diving to 300 fsw. But we would accept use of the unit to the depth to which it has been tested.

D.Long: There was a time at which anything that occurred in diving really came from the Navy and it was downloaded into the civilian environment. Along came the oil industry, and it is now absolutely reversed. If you look at everything that the Navy uses, it started off in the offshore oil world, and then went back into the military. There is nothing wrong with having test procedures before you put equipment on people. I'm one of the chief outlaws out there. We're going to go out and try to find something and make it work. We're going to find out then what is wrong with it and try to fix it. We're going to try to do all of that testing in evolution as opposed to testing necessarily. Just understand that if you wait until you can get a specification and wait until you can get the manned testing and the lab testing, you are going to be waiting a long time before you get to 300 feet. There has to be some kind of an accommodation and mutual respect and appreciation for both sides of that coin. Having said that, I want to change the subject and add one other thing. A benefit of using a tethered diver that you don't get with the other methods is that the diver himself can carry a video camera on his helmet. If he is only going to be at 300 feet for 20 minutes, he can then record everything that he sees and looks at and go back later on and review the footage after the dive is over. This also serves as backup. There are some inexpensive, reliable cameras or recording systems available in the commercial world that can be carried on the diver. For the scientific diver there’s an added advantage to have an umbilical situation in which he can record what he sees and then review it afterwards.

M.Gernhardt: Likewise for recording the voice too instead of writing something down.

B.Morgan: I got the band mask all done and I was sneaking in the back door of NEDU up in the Washington Navy Yard. The guys really liked the hat. Before the oil company guys took them, I was making metal helmets for the oil industry. They agreed to test it under the table at NEDU so they could moonlight with it if I would sell them so many at such a price. These are the individual guys, it was John Harter, before Middleton. Anyway, we snuck six of them in there and ran the full gambit of tests, which they passed. Then I went to the petroleum industry, but that was all under the table. I couldn't get away with that anymore.

D.Southerland: We're a more honorable group now.

D.Long: Bev, would you accept that you were an outlaw at the time?

B.Morgan: Well, I used to sell hats to the chiefs for 50 bucks a chit because they could sign 50 dollar chits. The only thing is they were 350 dollars, so I had to sell them seven chits.

J.Styron: Well, I just thought about this example after Dick just brought that up. The Navy took some of the gear from the oil fields, and I believe they tested the Superlite 17 and changed it to the 21 because apparently it wasn't safe as a 17. Commercial divers are using the 17 all over the world and Navy divers are still using 21s. You've just got to look at the different aspects of what we do. A lot of rebreathers are built in garages and I wouldn't even go into the garage they were built in. But there are some that may not meet military spec (Navy standards) for everything, but divers use them and live. That's how things evolved to the next step.

W.Gerth: Well, yes, people smoke and they live, too.

J.Styron: Well, not long.

W.Gerth: My point was that the Navy doesn't promulgate something for fleet use cavalierly. Certainly initial development of gear ought to happen and be done by outlaws, in garages, but they ought not be then promulgated for widespread use until they are subjected to thorough testing. That's all very well and good. The 17 needed a little modification for it to make Navy standards. Now the 21 is a very successful rig in the Navy.

B.Morgan: Not to knock how you guys do the rebreathers, but I did my share of running up and down stairs on a rebreather until anoxia set in just to see, because I knew I couldn't tell you when it set in. Without a breathing machine, you can't test any kind of breathing gear. Believe me, the 17 ran the gambit before the 21 came along and before it was introduced to the commercial field, the 17 got run on NEDU breathing machines.

W.Gerth: An even more important issue where this validation is critical is in dive computers. I am amazed you guys dive these things with algorithms that you neither understand or have seen any validation for. We couldn't give those sorts of computers to our divers.

M.Lang: In these workshop settings we often hear that there is no data or comments about the quality of the data. The scientific diving community has operational exposure data that we consider every bit as valuable as experimental data, for the following reasons: we know exactly what the time/depth profiles were because they are downloaded from these precise dive computers/recorders; and, we know the outcomes (DCS or no DCS) for those particular profiles. Further, we're not really validating the tables using our scientists as guinea pigs. We are far inside that outer maximal envelope. Like a speedometer that goes to 200 miles per hour. If you are only going to drive your car to 60 mph, you don't have to test it to 200 miles per hour.

W.Gerth: Are these no-D dives?

M.Lang: The AAUS data shows that the majority are no D-dives.

W.Gerth: Fine. At your last workshop I showed you that the computers are very conservative for no-D dives. But when you start asking them to calculate decompression, things start going sideways.

M.Lang: As a matter of fact, for single dives, if you compare the no-decompression limits, the dive computers (with few exceptions) are more conservative than the U.S. Navy tables for square-wave profiles.

M.Gernhardt: I would have to strongly endorse what Wayne is saying. Karl gave the presentation on the dive computers that struck me as almost comical with respect to trying to apply those algorithms to a complex long deco dive.

M.Lang: I'm not referring to mixed gas dive computers, that's clear. We're talking about conservative air dive computers.

M.Gernhardt: If one of your desires is to use surface-supplied helium diving to do wall investigations, most of the commercial tables are not set up to take advantage of multiple depth diving. The partial pressure tables, the alpha tables, they're not really set up for that. As I pointed out with my charts, there's advantages in multi-depth multi-gas. It's not clear to me that the decompression methods exist right now to fully exploit the kind of research you are doing. Some more work needs to be done in that area. Let's put it this way, it's not as safe nor efficient if you are just going to do a 20-minute dive to 300 feet. I would much rather do a multi-level dive as I was describing. It should ultimately be safer when validated and give you a lot more bottom time.

W.Gerth: One of the take-home messages I was trying to make was that particularly for dives that are done with in-water decompression to depths deeper than 250 feet on heliox, you are going to be facing DCS risks that are higher than those that you are used to dealing with at this point with the kind of diving you are doing now.

M.Gernhardt: With the existing pressure tables.

W.Gerth: Certainly with the Navy tables. I don't think we're going to be able to engineer schedules even with better models that give you the balance between O_2 toxicity, DCS risk, and acceptable in-water decompression times without having higher DCS risks than those that you are used to.

M.Gernhardt: You are saying full in-water decompression versus sur-D-O_2?

W.Gerth: Yes.

M.Gernhardt: Okay, I agree with that. If you go to sur-D-O_2, I think you can do it as safe.

W.Gerth: What I said was DCS risk will likely remain an issue in surface-supplied heliox diving with operationally acceptable bottom times and in-water decompression particularly for dives to depths deeper than 250 feet. In surface-supplied HeO_2 diving with operationally acceptable bottom times if you do a spike dive to 300 feet, six minutes down and then come up with operationally acceptable bottom times and in-water decompression.

M.Lang: Tables or bottom times?

W.Gerth: Bottom times and in-water decompression. I'm going to go back into your sentence but let me finish this one first. It won't make sense until I go back. Particularly for dives to depths deeper than 250 feet. That's how you end that sentence. Now in order to make that sentence complete, we have to say DCS risk will likely remain an issue. You are going to have to think about it. You are not going to be at .01 or .02. And following from that then I just have a point to make. The issue of having the requirement of an on-site chamber for treatment follows from this. I would recommend that you not consider doing dives to those depths without an onsite treatment capability.

M.Lang: Any dives, or dives with a certain level of severity?

W.Gerth: I would say any dives.

M.Lang: We need some exposure times coupled to this, not just maximum depth.

W.Gerth: The thing is, you could get stuck on the bottom. When you are doing those kinds of dives, you ought to have a chamber around because you can't necessarily predict problems.

G.Beyerstein: A decompression chamber is a necessary component of mixed gas diving systems.

W.Gerth: Yes, you are going to be on helium at that depth.

D.Southerland: Two comments. One, if you do sur-D-O_2, then you are going to have a chamber there so it really only affects situations where you are going to do all your decompression in water. The other thing is the chamber has nothing to do with your DCS risk. It only comes with the consequences if you happen to have decompression sickness and whether you are going to end up with any sort of sequelae. It is one of those things where when you look at the hazard you've already had the event occur. Now what are the consequences of that event occurring?

M.Gernhardt: The point that Wayne and I are making is that if you have a chamber and can do sur-D-O_2, you can do more conservative decompression. So in that regard, it does lower your DCS risk.

P.Lobel: As a working scientist, the only thing I would say about possibly having an absolute requirement for a chamber is you are going to create a lot of bandit scientists, people like Rich Pyle and others. Is this just for surface supplied diving? We are talking about diving at these depths. Do we want to link surface-supplied diving strictly to a chamber or do we see this being expanded to what does it take to work at these depths and there are various tools. One of the tools is surface-supplied diving. Other tools are open-circuit, regular scuba, rebreather, etc. First of all, I would agree. I would love to have a chamber on site all the time anywhere I'm diving. That is a good band-aid if you need it. But it is not practical in the real world for a lot of the things we're doing. I worry about putting requirements like that forward that are really going to be unattainable at our funding levels.

M.Lang: With tongue firmly planted in cheek I would make the observation that we'll still have the same incident rate we have now because no one will be able to dive to 300 fsw because they can't put a chamber on-site.

W.Gerth: Everybody keeps bringing up Richard Pyle who is walking today only because he was treated. The guy has been severely bent. I don't think you should hold him up as an example of how to dive to these depths safely.

P.Lobel: No, I wasn't. I was saying he was a bandit diver who was out there doing it outside the system.

W.Gerth: I get the sense of out of this meeting is that I've got a bunch of scientific divers here that are asking for AAUS sanction to do things that they are going to do anyway.

M.Lang: Not in my program they are not.

W.Gerth: The AAUS is not obligated to endorse all sorts of diving activity that you guys may do. I think that you are going to reach a point where the AAUS is going to make a statement that we will ratify or endorse a certain kind of diving with a certain kind of equipment and everything else as being within the constraints that we consider safe and acceptable. If you want to do something else, fine, but you are out on your own then.

M.Lang: I believe it to be a compromise. It has been this way with our scientific diving standards since 1951. It's a given what you just said.

W.Gerth: If you are going to have a higher DCS risk, then I think you should have a bullet there that says we recommend that there be on-site chambers for dives to this kind of depth.

M.Lang: So only depth? Do you want to qualify the bottom times? For a two-minute dive at maximum depth of 300 foot, do we still need a chamber?

W.Gerth: The problem is you get deeper and deeper and everything is so time compressed. What is the difference between two and three minutes? What is the difference between ten and twelve? It can be enormous. I would say put no time there. Once you have gotten to that depth, you're in another world.

M.Lang: Should we remove "operationally acceptable"? That really doesn't say anything because that's a different value to different people, right?

W.Gerth: Well, I mean non-exceptional exposures, 300 feet for 30 minutes is the Navy maximum.

M.Gernhardt: The main point, I think, Wayne wanted to make is that the DCS risks for surface-based helium diving with in-water decompression are likely to be higher than what you have experienced in your programs. They are an issue that needs to be addressed with respect to what you consider to be acceptable risk, with respect to conservative measures that you might choose to implement with them. I would go further to say I personally don't think that you are going to be very happy with surface-based helium diving techniques if you are only doing single-depth dives. You are going to get 15 minutes at 300 feet and then 20 minutes at 250 and then do another dive and get 20 minutes at 180 feet. It's not going to be very efficient. My point was that we probably need to, in a phased manner, implement methods that exploit multi-depth and multi-gases because otherwise, it is going to be short. The risks are higher that those associated with other kinds of scientific diving, those that you are doing now.

W.Gerth: The best information we have from all sectors is that there are increased risks of DCS associated with deep mixed gas dives. You are on the right track.

M.Lang: From normal AAUS operations?

A.Brubakk: Certainly this goes for all dives.

G.Beyerstein: That depends on the quality of the table.

W.Gerth: I don't think we can make a table that will give you acceptable decompressions and keep the $CNSO_2$ toxicity risk low that will give you a risk of .0001.

G.Beyerstein: I actually think you can. For example, with the UK, they had this notion that there was a depth exposure limit that is an end variant. But it's not the exposure that gives you the DCS. You can saturate and come up safely.

W.Gerth: If you give me all the time in the world to decompress you, I can get you up from any depth. That's what I mean by operationally acceptable. If you've got five minutes of bottom time and it takes you three days to decompress at the risk you want, you're not going to want to do that kind of diving very much.

G.Beyerstein: Include "surface-supplied diving."

JP.Imbert: Surface-oriented. What about the deep scuba dive?

M.Lang: Let's agree to first document what we find at this workshop Next, we'll fine-tune the wording of the particular recommendations. Is there a national need to perform research at 300 fsw or greater? Is that a finding of what was presented here?

J.Styron: We should not put "at 300 feet or greater" because that suggests that we are already at 300 feet doing much work, which we're not. We should set it at the maximum AAUS limit compressed air scuba at 190 fsw, "beyond the accepted AAUS depth …"

M.Gernhardt: What is that, 190 fsw? Is that your current level? You probably want to work in that with a human in situ versus ROVs and so forth.

B.Morgan: Is that 190 fsw on air?

M.Lang: That's correct. That's the operating window that the federal government's Department of Labor, in the scientific diving exemption from OSHA commercial diving regulations, allows us to work in. This is based on the scientific diving statistics submitted in support of the exemption from 1965 to 1982, based on a DCS incident rate of 1 hit per 100,000 dives.

W.Gerth: That's another factor for using helium as the key point as well as depth.

M.Lang: That's a good point except nobody can really tell us why it was exactly 190 fsw instead of 180 or 200.

B.Morgan: Because that's what the Navy says.

D.Southerland: Everybody is talking about not including 300 fsw, but it seemed like 300 feet was mentioned quite a bit. So that means we only need to go to 200 fsw.

Q.Dokken: You might just want to say beyond 190 fsw, but that statement captures it right there. Don't set a bottom limit because I guarantee you in five years, we'll be well beyond that.

M.Lang: Does that make sense to everyone? The discussion in these proceedings will reflect why we decided on 190 fsw, basically because that is a natural cut off (OSHA) and there was a rationale from the Navy to limit air diving to 190 fsw. Properly controlled surface-supplied diving is the safest method was also suggested…compared to what?

JP.Imbert: It is one documented method of intervention with reasonable safety record. For the moment, it is the one with the most impressive track record.

M.Gernhardt: I would be comfortable saying properly controlled surface-supplied helium oxygen, or for helium-oxygen diving, properly controlled surface-supplied diving is the safest method.

JP.Imbert: It is one safe method derived from our experience with commercial diving. It would be very unsafe in other conditions. We know for sure we have one way of intervention.

B.Morgan: I wouldn't shut out the rebreather divers by saying that it is the safest. It offers operational and safety advantages.

Q.Dokken: Well, we don't even know that. I mean those are all subjective statements.

M.Lang: We need to look at the exposure data.

D.Dinsmore: How about "is a safe and viable method?"

B.Morgan: It's one of the safe and viable methods. Leave it open.

M.Lang: Can we use "effective" instead of safe because we don't want to use the word safe in any of these recommendations.

B.Morgan: Just put down is a viable method.

M.Lang: A viable method to do what?

M.Gernhardt: Beyond 190 foot, for deeper diving.

G.Beyerstein: We should put mixed gas in that statement. That gives you nitrox, trimix, whatever.

M.Lang: On the table is a suggestion to include the gas.

B.Stinton: Put another bullet under the first one that says below 190 feet using compressed air, helium-based mixtures are more appropriate.

G.Beyerstein: You mentioned helium. You are limiting your mixes. Mixed gas covers everything.

W.Gerth: Getting back to bullet one for just a second. There is a national need for scientific divers to get to depths deeper than 190 feet for research.

J.Styron: The emphasis is on divers. I got to get guys in the water. I could put submarines to 1,000 feet, no sweat.

W.Gerth: The key here is the national need for scientific divers to perform research. Scientific divers being guys wearing gear or breathing or wet because I can do scientific research at 1,000 feet from a submarine.

G.Egstrom: We need to say method to conduct deeper scientific diving research.

W.Gerth: To tie it to the first bullet, say a viable method to conduct such diving. Because we just said scientific diving at depths beyond 190 feet. Properly controlled mixed gas diving is a viable method to conduct such dives.

M.Gernhardt: We ought to get the basic concepts down and keep moving forward and then come back and clean up the words. I still think it is very good.

M.Lang: Some marine science objectives are not compatible with surface-supplied diving. Is that a finding of what was presented here?

A.Marsh: A lot of them could be made compatible but there are some that aren't.

B.Morgan: Not one type of equipment will do all the work.

G.Beyerstein: Delete the word compatible, may not be optimal.

B.Morgan: The main thing is you just don't want to shut the door on any particular type of diving.

M.Lang: Supported by surface-supplied diving? Achieved?

G.Beyerstein: No, that makes it absolute. That's why I said optimal. You could do it but it is not the best way.

A.Marsh: I thought compatible was the word.

K.Huggins: Surface-supplied diving may not be applicable to all marine science objectives.

W.Gerth: May not be met; you meet objectives by doing things. If your objectives aren't compatible with what you are doing, may not be met by this methodology.

G.Beyerstein: I would reverse it. Surface-supplied diving may not meet all the needs of some marine science objectives.

W.Gerth: Okay. That's fine, too. As Mike Gernhardt just said, we've got the basic idea there now.

M.Lang: Is it a finding of this workshop that research grant funding levels are inconsistent with the support required to 300-foot sea level diving?

P.Lobel: That's a hard thing to say because you are talking about existing funding for an existing program. On the other hand, I think that if a scientist came forward, as you said before, and really laid out a clear scientific need to get those depths and applied to NSF, they would get the funding to do it.

M.Lang: Should we say anything about funding from the presentations we heard?

M.Slattery: I don't think so.

B.Morgan: I think you can get to 300 feet on existing research funding.

M.Lang: Does anyone think that we should report something about funding as a finding? Who agrees with that? So there are quite a few people who do agree that some funding wording be included.

B.Morgan: The main thing you have to be guarded about is don't put something in there that some guy in an office with a green eyeshade on can say see, there's not enough money to do it.

D.Kesling: Say there aren't current funding levels for the systems that have been alluded to for surface-supplied diving, for these heliox dives, with onsite chambers.

M.Slattery: But there are other ways to get to 300 fsw.

P.Lobel: What we might want to say is that diving at 300 feet requires higher than normal funding levels than diving with regular scuba. You have to recognize that increased technology comes with increased costs. We don't want to whine about the need for more money. Somebody in accounting will be saying this is just a ploy to get more money into marine science.

B.Morgan: Yes, the way you are saying it is right.

Q.Dokken: We need to go back to funding support for scientific diving beyond 190 fsw will require increased expenditure of funding.

P.Lobel: I would just say higher levels of funding than diving with normal scuba.

D.Southerland: Drop the funding support required for it. Say scientific diving, it's repetitive.

M.Lang: We still need support in there somewhere, right?

Q.Dokken: Scientific diving beyond 190 fsw will require increased funding allocations.

M.Lang: Back to the increased risk business.

W.Gerth: Particularly with in-water decompression.

JP.Imbert: Then there should be a point saying that the old tables are too old and the new tables are too new. Before any operation there should be an evaluation of diving procedure, a careful risk analysis in order to make a decision what to use.

W.Gerth: It's been done with the Navy tables. I would not like to see that there.

M.Gernhardt: There are two points: Navy tables and commercial tables exist now that are adequately safe to do 15 or 20-minute bottom times, single depth. I don't think you are going to be happy with that. We ought to think about a phased program to exploit the decompression advantages associated with multi-level and multi-gas. If you want to do 15 minutes at 300 feet and then 20 minutes at 200 feet on two separate dives, it's going to kill your efficiency. Start with established methods. I wouldn't even propose that you develop a new method until you have established that this is even a viable technique for what you are trying to do. But once you have, then you need to optimize the decompression method for the type of diving. Right now there is no such table.

W.Gerth: Well, you won't have a table that does that. What you will need then is a computer that works well.

M.Gernhardt: There actually are tables in our table format that would be very appropriate for this.

W.Gerth: You can't tell me your table handles all the possible intermediate depths involved.

M.Gernhardt: It does.

M.Lang: We need to include something about decompression optimization, addressed by both Brubakk and Gernhardt.

K.Huggins: On the second point, an appropriate operational and emergency response method needs to be incorporated to deal with these risks.

M.Lang: There are increased DCS risks associated with mixed gas surface-supplied diving.

J.Dobarro: It is associated with mixed gas diving. Aren't you implying that there is no increased risk with other modes of going this deep?

M.Lang: Should we omit surface-supplied diving?

A. Brubakk: Mixed gas bounce dives, that's a good point. You can't do it with saturation. What we're talking about here is mixed gas bounce dives, isn't it?

W.Gerth: We're talking about sub saturation dives.

A.Brubakk: If you want to put in something about optimization, you could say that the possibilities of optimizing these procedures should be explored.

M.Lang: Intuitively, yes. There is an increased risk. We see that with single dive, no-decompression bottom times. The deeper you go, the less bottom time you have. We can't really attach a percentage increase in risk, this really doesn't say anything.

B.Morgan: Just add “from the surface.”

W.Gerth: You talked about mitigating risks of not having a chamber by performing very conservative dives. What that means is within tables, instead of going to 60 feet for 60 minutes, you are going to 52 feet and using the 60 minute schedule. At 300 feet, you don't have that kind of play. So the difference between five and eight minutes or between 20 and 25 is huge. You won't be able to get the kind of safety mitigation as easily in these deep dives as you could in the shallower dives.

M.Gernhardt: In fact, skipping the time and depth can actually make it worse in some cases.

W.Gerth: You are in a different arena here. It's not trivial.

M.Gernhardt: Another argument for a chamber is once you've spent 20 minutes on helium or even 15 minutes, coming straight up like you could on an air dive isn't really an option.

K.Huggins: Appropriate operational and emergency response method needs to be incorporated to deal with these risks.

B.Morgan: Add from the surface at the end of the first sentence.

W.Gerth: With deep mixed gas dives from the surface?

B.Morgan: I can go down in a bell and there is no increased risk.

W.Gerth: Aren't we talking sub-saturation dives?

M.Lang: We're back to surface-supplied diving. You leave the surface, you are down on a hose.

L.Somers: You've got to leave the surface.

M.Lang: Everything comes from the surface.

B.Morgan: Except bell diving.

K.Huggins: Actually, bell diving would be an appropriate operational response to mitigate the problems.

L.Somers: We're talking about surface-based diving.

W.Gerth: We need to set the context for all these bullets up early. The bottom line is we're talking sub-saturation exposures. In the business, at least we all know the difference between sat dives and sub-sat dives.

M.Lang: That is valid.

M.Gernhardt: It may be time to develop a new set of decompression tables or a new algorithm for surface-supplied helium diving from first principles with modern probabilistic approaches to decompression. I can do that.

M.Lang: And we can't conduct deep diving science until that is done by the Navy 20 years out?

W.Gerth: Development of a new set of decompression tables for this type of diving ought to be considered.

M.Gernhardt: And either decompression tables or new decompression methods.

M.Lang: Procedures? Should optimization be in there somewhere?

M.Gernhardt: I wouldn't use the word optimize.

W.Gerth: The reason is that the word means different things to Alf and to me.

A.Brubakk: Not necessarily.

M.Gernhardt: Not necessarily? I'm a fan of tables over computers but I think procedures or methods would encompass tables and/or look up computer programs that are on the surface versus a diver-warrant computer. I mean I don't think you want to tie yourself in to any particular box right now. Should be considered for this type of diving. My point is once you sort it out with just the standard air techniques that you can use surface-supplied diving, then you are going to want to go to this more optimized method.

W.Gerth: Precede that bullet we just finished with a statement that Mike Gernhardt just said before: existing procedures can be, but they may not be optimal.

M.Gernhardt: Existing procedures are adequate to investigate use of surface-supplied diving for scientific research. They're okay to initiate, but that the theme is over time you're going to want something better than what exists right now.

K.Huggins: The question is existing procedures. We have at least four dive computers. We've got about 20 different decompression software packages out there. Those are existing procedures. Do we want to say that those are currently available and acceptable, but not optimal?

W.Gerth: Excellent point. No, we don't. We could say existing U.S. Navy and commercial diving procedures.

G.Beyerstein: Scratch that bullet. At the bottom of the next one just add "should be considered to optimize." What you're trying to do is express that you want to fit tables to the mission profile.

JP.Imbert: I believe it should be a statement recalling that commercial diving and military diving have already designed tables that are in use. So that's a starting point, and then you develop maybe the need for something better.

W.Gerth: That's Jean-Pierre's point. We don't need to tell people that they can't do this now. We need to say there are ways to do it now. They just may not be the most efficient.

M.Gernhardt: U.S. military and commercial? I wouldn't rule out the Canadian forces.

W.Gerth: Fair enough, military and commercial procedures.

M.Gernhardt: decompression procedures have been established.

W.Gerth: No, we don't want the computers.

JP.Imbert: Use and validate. Satisfactory level.

G.Smith: "are acceptable"

M.Gernhardt: And then make the point that consideration be given to developing decompression methods customized for the scientific mission.

M.Lang: Consideration should be given to the development of new decompression procedures for scientific diving?

M.Gernhardt: "to better fit the scientific diving mission" since we're saying we can start out with existing procedures.

M.Lang: Consideration should be given to the development of new decompression procedures to better fit the scientific diving mission. For subsaturation diving exposures there is a national need for scientific divers to perform research at depths beyond the 190 foot compressed air scuba limit. Properly controlled mixed gas surface-supplied diving is a viable method to conduct such dives.

J.Dobarro: Take out the "gas surface-supplied diving" there too, because of re-breathers.

G.Beyerstein: We're just saying it's a viable method and we're talking about mixed gas surface-supplied diving through the rest of it here.

D.Southerland: The focus of the meeting was on surface-supplied diving.

G.Beyerstein: Can we add on the second bullet something to the effect that this is normally satisfied by the presence of an on-site decompression chamber? It's not closing it off, but it's stating that it should be there.

M.Lang: Do we need to include the decompression chamber?

J.Godfrey: That's included in the emergency response methods.

G.Beyerstein: That can be anything. That can be a chamber 20 miles away, and that's not adequate.

J.Godfrey: Well, you said appropriate.

G.Beyerstein: It leaves it too open to say appropriate.

M.Lang: The Aquarius habitat functions as a chamber for decompression from saturation to the surface. If the diver has a problem after being on the surface, there is no chamber on site.

G.Beyerstein: That's not mixed-gas surface-supplied diving.

M.Lang: On the table is the suggestion to include something about decompression chambers. Were we presented with data or was that discussed at length?

K.Huggins: There's enough division in this group that there needs to be a mention of it at some point.

M.Lang: Several individuals objected strongly that they couldn't do their work if that was to become a requirement.

K.Huggins: Some people said that chambers are required. Others have said because of what they need to do and what they have available, they can't do that. A balance needs to be met or decisions need to be made.

G.Beyerstein: But that's already taken care of by saying appropriate operational emergency response methods need to be incorporated. You can choose those.

G.Egstrom: If you're doing it right, do you need a chamber on site? Or do you need one that's available within a reasonable time?

J.Godfrey: "Appropriate operational emergency response methods need to be incorporated to mitigate these risks. On site chambers have been suggested."

M.Lang: I would suggest have been traditionally used in commercial and military diving. Somehow qualify what the presence of a chamber is versus boxing us back out again to where we were 20 years ago.

M.Gernhardt: We might say something as general as the conditions under which a chamber is required need to be defined. As a group you might decide that for these kinds of dives where we have 400 already, we never had a bend. You might get yourselves comfortable enough to where you don't want a chamber there.

JP.Imbert: I would like to suggest just a safety plan depending on how long it will take to bring the diver to the chamber. You may have to decide to have the chamber right on site, or maybe you rely on a helicopter to fly the diver to the nearest chamber. It's really a matter of committing a resource.

M.Lang: I'd like to again make the observation to not lose sight of the fact that our missions in commercial, military, recreational, and scientific diving are very different. If we include a chamber required on site, the areas of high interest to U.S. science in biodiversity is in the South Pacific, where we're not going to be able to have a chamber on site with every scientific diving project. We'll determine, a priori, our acceptable level of risk and adjust our profiles accordingly.

M.Gernhardt: Unless you have a vessel that steams over there with the surface-supplied gear, which is probably what you want to do.

W.Gerth: I think it behooves us then to make a statement that without a chamber you are accepting higher risks for this sort of diving, because that's a fact. What we're trying to do is write the requirements of what you would want to do operationally. You don't have to have a chamber because you can't afford it, but what that means is you have to accept a higher risk of some catastrophe that you won't be able to deal with than you have to in other cases in your diving. You need to acknowledge that.

M.Lang: We already have acknowledged that there are increased risks associated with deep mixed gas diving.

W.Gerth: Or DCS risk, okay.

A.Brubakk: Not necessarily, because the point here is that the probability that something will happen is admittedly quite low. However, the consequences of having a problem from 300 feet will probably be quite severe. You have to weigh the possible consequences of not being able to treat someone. You have to add the probability that something will happen and the consequence if something goes wrong. So that is the risk assessment.

M.Lang: The risk assessment of what I just did with my Diving Officer staff in December in Belize, 190 foot compressed air dives without chamber on site was routine and acceptable. We assessed that risk and decided for training purposes and for our science objectives that it was worth the risk. It doesn't make us outlaws, cavalier or just lucky.

M.Gernhardt: What kind of bottom time?

M.Lang: They're what commercial divers call bounce dives. 190 feet, three minutes on the bottom and working our multi-level way right back up the wall.

M.Gernhardt: That's a very safe dive.

M.Lang: Again, maimum depth has to be coupled with a description of the type of dive and decompression stress. I am concerned that with general statements, particularly about chambers, we're going to defeat the whole science purpose.

M.Gernhardt: I think you have a very valid point.

M.Lang: Thank you.

M.Gernhardt: Where the commercial guys are coming from is with the U.S. Navy partial pressure, single depth dives or even alphas, you have a higher risk of a serious DCS incidence and you want a chamber. I agree that from your point of view, depending on the specifics of the operation, the dive profile, proximity to chamber, all of that probably needs to be taken into consideration.

M.Lang: We do that through our dive plan authorization process, a risk assessment.

A.Brubakk: But can't we simply add a sentence saying that the need for an on-site chamber should be evaluated?

M.Gernhardt: The availability should be addressed during operational planning to cover that. And the folks that are doing 300 foot dives, is that sanctioned by NOAA?

G.Egstrom: If you're going to do a risk assessment, you're going to have to get into this acceptable risk. That's something that needs to be done specifically for each operation.

M.Lang: Which we do already, that's the scientific diving community's point.

G.Egstrom: So, I don't know. I think you're just going around in circles.

M.Gernhardt: Gary, how strong do you feel that the word "chamber" even needs to be in here right now?

G.Beyerstein: I feel very strongly about it because you're talking about mixed gas. You're not talking about compressed air, and it's an entirely different animal. Mike Gernhardt said himself, just a few minutes down there on helium, and if you're into a serious problem and have to bring somebody to the surface without a chamber, not good.

M.Gernhardt: The problem I have, Michael, is the cultures. In the commercial world, with the kind of diving that we're talking about you guys doing, we know we need a chamber. Now, you guys have experience and you're doing in-water and you're doing light exercise, and a bunch of Jesus factors are helping you out, and you know, you have mild luck. It's good.

M.Lang: Point made. I believe that it fits up here under emergency response methods because I don't authorize a single dive plan without information on the nearest medical facility, nearest chamber, how you're going to get there and who you're going to call.

M.Gernhardt: Then just put appropriate operational emergency response methods including consideration of on-site chambers. Don't say you have to have one, but just consider it.

M.Lang: On-site chamber availability doesn't mean you have to do it, but you ought to consider it.

M.Gernhardt: If you're 20 minutes away, you're not going to get to something 20 minutes away no matter what. It's going to be an hour or more.

M.Lang: Well, that's not true. Off Catalina you can get a 300 foot depth not too far away and get to the chamber within minutes.

G.Beyerstein: Figure it out. Think about bringing an unconscious diver up, getting him over the side, taking him to that chamber and loading him up. How long is it going to be? It's going to be a lot more than 20 minutes I guarantee you.

M.Gernhardt: I'm reasonably happy with the wording we've got there now.

G.Beyerstein: I'm happy with that.

M.Lang: Can everybody live with that? Anybody have any heartburn with that or any additional comment? No going back now that we've all agreed.

P.Lobel: Scientific personnel selection and training for mixed gas in deep diving requires enhanced criteria beyond standard scientific scuba. There's a higher standard of physical and psychological requirements for a deep diver than normal shallow water open scuba.

G.Beyerstein: Extensive training in diver selection is necessary for any deep mixed gas surface-supplied diving operation.

M.Gernhardt: Diver selection and training standards for mixed gas diving should be more stringent than open circuit scuba?

M.Lang: We already have scientific standards for mixed gas and re-breathers. What we're really trying to say here is that not everyone can do it, right?

G.Egstrom: Diver training considerations must be part of the overall risk assessment.

G.Beyerstein No, that a mixed gas diver can go ahead and dive on some gas and not others in enhanced training, and I disagree with that. I think that any time you're going to dive mixed gas you get a training and a selection regardless of the diving issue.

Q.Dokken: I believe you could say mixed gas selection and training considerations must consider the unique challenges to advanced diving strategies or technology.

P.Lobel: Basically we want to say a higher standard of personnel selection and training is required.

M.Gernhardt: You wouldn't have somebody that wasn't qualified to do it do it, right? So you're handling that through your own filter systems.

J.Styron: And that's through each individual, in AAUS standards and each individual training.

G.Beyerstein: How about mixed gas diver selection and training considerations are enhanced for this diving mode? That's not saying you do anything. It's just a statement.

M.Gernhardt: It sounds like you're doing this already, but you don't have it written down anywhere, and it strikes me that you might want to write it down.

P.Lobel: You really want to have it written down because otherwise everyone who is a standard open circuit scuba diver is going to say, "I have a right to dive deep," and in the university systems, you can't be totally politically correct. You've got to be able to say not every diver can do this.

M.Lang: Mixed gas diver selection is discriminatory! How's that?

P.Lobel: Not politically correct or handicapped accessible.

M.Lang: We should, in fact, say something because we've discussed the selection and training procedures on several occasions.

M.Gernhardt: It serves your purpose to write this down and I don't think it hurts you. Mixed gas diver selection, training, and proficiency standards are necessarily more stringent than those associated with air diving, and if anybody disagrees with that, raise your hand.

G.Beyerstein: Since you don't ever mention standards, why not say requirements? Requirements I think are better than criteria.

P.Lobel: We don't hurt ourselves by writing that down, it h helps us.

J.Styron: I'm more than happy to tell a diver no.

M.Lang: Any additional heartburn with this, anybody?

P.Lobel: I would just add surface-supplied diver. It's identified in the mixed gas standards for open circuit in the AAUS manual. It's the same kind of training proficiency. So you're identifying a target group here. You're talking about a technology. Otherwise, it's too generalized.

M.Gernhardt: We probably need to have a better diver if he's doing closed-circuit scuba for this than surface-supplied diving, but that's the argument for going to surface-supplied diving. They don't have to be as good a diver because they've got somebody on the surface taking care of them versus them having to make all of the decisions themselves under water.

G.Smith: After selection and training, proficiency requirements should be competency based.

G.Beyerstein: Isn't proficiency the same as competency based?

G.Smith: Not necessarily, but we could leave out proficiency if we said competency based.

K.Shreeves: Aren't all of your standards competency based though? At least the original point of this recommendation was that you're trying to say in nice words that you aren’t all going to be able to do this, so that's why we want to leave in “more stringent than for air diving.”

M.Lang: That's right. Looking back through the presentations and from your notes, are there any other messages we can recommend?

G.Egstrom: Are we going to say anything about the training for the specific requirements of each project? I heard a dozen times that projects are different. They require training and preparation, every one of them.

L.Somers: Basically I said has its own unique set of criteria for planning a dive.

G.Egstrom: I'm thinking in terms of diver qualifications and the technology selection and all of that has to look specifically at the requirements of the mission. That's why we have to accept that there are different solutions to different problems.

M.Gerhardt: I agree with that. For example, some people aren't going to like to go right into a Superlite 17 because it's a big change from an open-circuit scuba regulator. A Heliox 18 band mask in warm water is probably going to be initially more amenable to the scuba diver than a 17. If you're diving cold water, you have to keep your ears dry and don't want to dive a 17. There won't be one set of gear for all operations.

W.Gerth: I get the sense here that we're trying to craft a set of findings that has got to be broad enough to encompass closed-circuit rebreathers. Is that true, or are we trying to limit our findings to subsaturation dives with surface-supplied gas? Because I'm going to have heartburn about several things here if we are trying to encompass closed-circuit rebreathers. We did not in this meeting, I think, put on the table all the issues that bear on the safety of those things.

B.Morgan: No, I think we're trying not to shut them out.

W.Gerth: But I don't want to encompass them in this either.

M.Gernhardt: Although, we don't want to rule out these hybrid systems that really offer a lot of promise for the closed-circuit diver.

W.Gerth: Then maybe we ought to say that. We've got to say we dealt with surface-supplied gas, thought that was the safest way to go. Closed-circuit rebreathers and hybrid systems were brought up as an option to get the best features of both diving modalities.

M.Lang: Well, some of these findings we're going to have to move into recommendations, because they are. Or, Findings and Recommendations, one category, which would save us a lot of pain.

K.Kohanowich: I think we do need to capture the fact that we considered the hybrids and the closed-circuit systems.

D.Southerland: Hybrids, CCRs, and SCRs warrant further consideration.

B.Konar: Shouldn't there also be a finding that says that CCRs are currently being used in the scientific community as an acknowledgement?

W.Gerth: Why are we afraid to say that surface-supplied diving is the safest way to do dives to these depths?

P.Lobel: A viable alternative.

M.Gernhardt: I actually believe that it is the safest, although not necessarily the best for all kinds of science.

M.Ward: We're talking about closed circuit re-breathers or semi-closed circuit re-breathers with surface-supplied diving. In other words, surface-supplied hybrid CCRs, that's what you want to have in there because you've already got closed-circuit rebreathers. That gives you surface-supplied bail-out capability and supply for the CCRs. Taking surface-supplied (supported) diving and putting it together with CCRs gives you the best of both worlds, a back-up capability and it will give you on bottom capability.

W.Gerth: Surface-supported diving because supplied implies you're sending the gas down there.

M.Ward: Right. If we use the word "supported," it could mean a lot of things, such as on-board telemetry or gases.

W.Gerth: Yes, but the critical figure is that the gas is supplied from the surface. You are unambiguously specifying that this surface-supplied diving means there's gas with it.

G.Beyerstein: Surface-supplied diving implying gas-supplied, that's one thing, but we also talked about having surface control by telemetry so that the diver doesn't have to concentrate on all of his readings down there.

L.Somers: Most people outside of this workshop that worked there years ago won't know truly what these are, and I don't know if this is really clearly defining. Surface-supplied diving is implying that the emergency gas is coming from the surface.

M.Ward: It can be both, emergency backup and supply gas all at the same time.

M.Gernhardt: You can always bail out at 1,000 feet. It's nominally surface reclaim with a closed circuit bail-out. There are all kinds of different hybrids.

M.Lang: Closed circuit rebreathers and trimix are currently being used in the scientific community and they should continue in their development.

M.Slattery: CCRs and open circuit trimix are currently being used in the science community. Properly controlled mixed gas surface-supplied diving is an additional viable method.

M.Gernhardt: The way that reads right now is it makes it sound like we're doing closed circuit and open circuit. The general theme here was that for the right kinds of scientific diving surface-supplied diving actually offers safety advantages.

B.Konar: Did we do a safety comparison?

M.Lang: We can only use “safest way” if we evaluate numbers of incidents or fatalities within the trimix open-circuit and rebreather dive data.

P.Lobel: Safety is a value judgment particularly dependent on the circumstances that you're operating in.

M.Lang: For a number of reasons we shouldn’t use “safe” in any of these findings or recommendations. Nothing is safe.

M.Gernhardt: Properly controlled mixed gas surface-supplied diving may offer additional operational advantages in some circumstances.

P.Lobel: Well, that becomes reductio ad absurdum.

M.Lang: Surface-supplied diving is a risk reduction method, right?

L.Somers: It can reduce some operational risk.

P.Lobel: Is there really data to show that? There are pros and cons to everything and unless we really do a comparison…

M.Lang: If we use the word "safer" or "safest" it means we're comparing modalities, and we haven’t done that here.

W.Gerth: Offers a reduced-risk method.

P.Lobel: I would just rephrase it the other way to say it offers the advantage of having independent surface control of the diver. Because when you talk about reducing risk, there's always a compromise and you're placing a value judgment that if you do this, it's potentially less risky than this other method. Whereas, in fact, what I heard was surface-supplied control offers advantages over some of these other issues.

W.Gerth: The advantage is a risk reduction. Why are we afraid to say that it's reduced risk? I'll be quiet after that.

P.Lobel: Sometimes the administrators or lawyers are focusing in on a few key sentences, and that's what they pick out and use. "Take the less risky method. No matter what, no longer use this method.”

W.Gerth: That's what the next bullet makes clear, this may not be a good option for some missions.

M.Lang: We don't want to negate the commercial diving experience. It's crystal clear that surface-supplied diving is a reduced risk management method for them and that's why they use it. Otherwise, the commercial guys would be diving rebreathers. There is more data for surface-supplied diving than any other modality.

K.Shreeves: The suggestion is “in some circumstances” and return that to a separate bullet. It may be a little redundant, but we'll all agree with it.

M.Lang: The next thing I was going to ask was regarding the flow of findings and recommendations, which need not necessarily be prioritized.

M.Gernhardt: Separate the findings and recommendations. Phased program should probably be the lead in bullet.

M.Lang: We can't iterate these findings and recommendations post-workshop. What we can’t reach consensus on here is not going to appear in print. Is there anything else we need to make a statement on?

G.Smith: I’m happy with this, it accurately reflects what we've discussed.

B.Konar: Consider a recommendation that there be a cost-benefit analysis showing the different ways that we can go to deeper depths. It would be beneficial to recommend a further study to actually compare these different methods.

M.Lang: The recommendations are for the scientific diving community and NOAA. We could synthesize and provide a table where we take the cost data for military, commercial, scientific for comparative purposes. How do you implement a cost benefit recommendation?

P.Lobel: If the proceedings are going out to the scientific community that isn't knowledgeable about these different methods, we need to have some sort of comparison.

M.Gernhardt: I would submit that we really haven't covered the details necessary to do that evaluation, and if you do it with the data presented here, it's going to say go with your open circuit because that's the cheapest dollar per bottom time, but if you factor in performance and risk and everything else, that's a more sophisticated study that I'm not sure we're prepared to do.

P.Lobel: That’s another step that we need to do. This could take a year and it's not going to slow anything down. I don't think any agency is going to step forward and provide the funding today to make this system operational for science within six months.

G.Smith: This proposed recommendation is beyond the scope of this panel.

G.Beyerstein: I'd like to add something about continuing development of dive computers. They're not validated and probably need more development.

M.Lang: That's not a true statement. We have published validation of several air diving computers, but perhaps not for mixed gas dive computers.

C.McDonald: One recommendation already states “development in emerging procedures.”

G.Beyerstein: Why don't we use “decompression procedures including tables and dive computers?”

C.McDonald: We went through that and decided to use the term "procedures" rather than "tables”, it’s inherent in the statement.

G.Smith: We have to limit the statement to mixed gas dive computer validation was not presented at this panel. We don't really know whether they're validated or not.

W.Gerth: The validation was not documented. They were given the opportunity but didn't do it.

M.Lang: Absence of evidence or evidence of absence? Many of those dive computers incorporate modified Bühlmann models. Is his work now not considered validated?

G.Beyerstein: Just say mixed gas computers need further investigation and development.

M.Lang: We heard a presentation by Brubakk and Gutvik who are doing further development, which is covered under procedures.

D.Long: Numerous people said if we're going to be using mixed gas we've got to have adequate thermal protection. We could add it in under that risk mitigation to include consideration of thermal protection.

P.Lobel: We could just add increased DCS risk and hypothermia.

D.Long: One issue is hypothermia, which we want to avoid obviously, but more importantly, the other issue is operational safety and for maintaining the scientists at their peak performance, they need to have adequate thermal protection.

M.Lang: Is everybody in agreement with the workshop’s findings and recommendations? All those in favor raise your hand. That constitutes a unanimous consensus and endorsement.

M.Lang: Gene Smith and I would like to again thank the Advanced Scientific Diving Workshop sponsors: the National Undersea Research Program, the National Marine Sanctuaries Program, the American Academy of Underwater Sciences, and the Smithsonian Office of the Under Secretary for Science. We also appreciate very much the effort of the workshop presenters and discussants for sharing their expertise.

Smithsonian Institution
Advanced Scientific Diving Workshop
February 23-24, 2006

Michael A. Lang and N. Eugene Smith, Co-Chairs

FINDINGS:

For sub-saturation diving exposures:

- There is a national need for scientific divers to perform research at depths beyond the 190 fsw compressed air scuba limit.
- CCRs and open-circuit trimix are currently being used in the scientific community.
- Properly controlled mixed gas surface-supplied diving offers a reduced-risk method to conduct such dives.
- Some marine science objectives may not be met by surface-supplied diving.
- Surface-supplied/supported CCRs and SCRs warrant further consideration.
- Scientific diving beyond 190 fsw will require increased funding allocations.
- There are increased DCS risks associated with deep mixed gas dives.
- Mixed gas diving requires adequate thermal protection.

RECOMMENDATIONS:

- A phased program using existing assets should be initiated, starting with training exposure of scientists to standard air surface-supplied diving.

- Appropriate operational and emergency response methods, including consideration of on-site chamber availability, need to be incorporated to mitigate the increased DCS risks.
- Existing military and commercial decompression procedures are acceptable; consideration should be given to the development of new decompression procedures to better fit the scientific diving mission.
- Mixed gas diver selection, training and proficiency requirements are necessarily more stringent than for air diving

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