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# An Evolution of Scientific Mixed Gas Diving Procedures at the National Park Service Submerged Resources Center

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## Abstract

The Submerged Resources Center (SRC) of the National Park Service has been conducting an assessment of sites of cultural significance in the Lake Mead Recreational Area since 2002. Many of the sites were flooded when Hoover Dam construction was completed and the reservoir filled, such as the aggregate plant and associated structures. Others have been deposited after Lake Mead filled, including a B-29 lost in 1948. Because many sites of interest are located at depths exceeding 150 ffw (45 msw), work initially began with ROV surveys. Later activity involved mixed gas training and in situ work with divers using heliox. Equipment profiles and techniques have evolved as subsequent phases of the project were fielded. Initially, open-circuit equipment was used, then mixed teams using closed-circuit rebreathers (CCRs) with the open-circuit divers, and most recently teams solely using CCRs. In addition to the SRC divers, participants from NOAA and NGOs have been involved. This paper will examine the background of the project, diving standards utilized for the heliox operations, and the procedures and safety concerns involved with teams using multiple modes of diving with mixed gas on these research operations.

## Introduction

The Submerged Resources Center (SRC) of the National Park Service (NPS) was originally established in 1980 as the Submerged Cultural Resources Unit. In 2000, their mission was expanded and their name changed. Their current mission is to provide direct support to superintendents and partners responsible for stewardship of submerged resources, and it enhances and facilitates public appreciation, access, understanding, and preservation of those resources.

In the past, SRC personnel have been involved in such projects as the original inventory of the ships sunk in Bikini Atoll as part of the 1946 atomic bomb tests (Delgado *et al.*, 1991), assessment of the U.S.S. *Arizona* (Lenihan *et al.*, 1989), investigation and raising of the Confederate submarine *H.L. Hunley* (Murphy *et al.*, 1998; Conlin and Russell 2006), documentation of the shipwrecks of Isle Royale (Lenihan, 1987), cataloguing the submerged cultural resources of Fort Jefferson (Murphy 1993), and examination and evaluation of the submerged artifacts of Nan Madol, Pohnpei (Lenihan, 2002). The vast majority of their diving work has been conducted at depths considered to be within reasonable air diving limits (150 fsw [45 msw]), however, many working dives have been made to deeper depths during the course of field operations. For example, dives in excess of 150 fsw (45 msw) were conducted in Isle Royale, Bikini, various reservoirs, and during examination of CSS Alabama sunk off Cherbourg France (Lenihan, 2002).

In 2002 they were asked by management of the Lake Mead National Recreational Area (LAME) to assist in the inventory and assessment of their submerged cultural resources. Lake Mead was formed when the Colorado River was impounded by the construction of Hoover Dam in 1935. There are three categories of submerged resources: preexisting structures unrelated to dam construction inundated by rising lake water, structures related to dam construction but subsequently flooded, and vessels sunk in the lake since flooding.

Lake Mead, at highest water mark, is as much as 589 ft (180 m) deep. The surface of the lake fluctuates depending on annual recharge from precipitation in the Rocky Mountains and other parts of the water basin and the amount of water released from the dam. In 2002, at the time SRC was requested to provide assistance, some sites of particular interest were located in as much as 240 ffw (80 mfw). No unit in the NPS, including SRC, had the capability to deploy working divers to these depths. Accordingly, SRC Chief Larry Murphy developed a training strategy to develop this capability to continue their mission of assessment, monitoring, preservation, and enforcement assistance to depths beyond 200 fsw (61 msw) in the safest manner possible, both in terms of project dive safety and minimization of longitudinal physiological consequences for career occupational scientific divers. This paper will cover the training, equipment, and procedures used to achieve this objective.

## Training

Five NPS divers were to be involved in the project. Three modes of diving were considered for the deep assessment work: surface supply, open-circuit SCUBA (OC), and closed-circuit rebreathers (CCRs). All divers had extensive (more than ten years) occupational experience in the use of commercial-type surface supplied equipment as well as open-circuit SCUBA. Surface supplied gas was rejected as an option because of the logistical requirements necessary and the restrictions to mobility required for archeological documentation of fragile sites like the B-29. Use of CCRs was similarly dismissed from immediate consideration because none of the divers had mixed gas or rebreather training, suitable equipment was unavailable within the NPS, and project deadlines did not allow sufficient time for this option to be researched and developed.

The anticipated working depths mandated that a helium-based breathing mixture be utilized. Replacing some of the nitrogen and possibly oxygen in air reduces inert gas narcosis at depth, as well as reducing the potential for CNS oxygen toxicity and physiological complications from long-term deep air exposures. Two options available were the use of heliox (a mixture of helium and oxygen) or trimix (a mixture containing nitrogen, helium, and oxygen). Use of either type of gas mixture offer positive safety aspects, but entails additional risk to the divers, including in part increased potential for hypoxia, hyperoxia, hypothermia, decompression sickness, high pressure nervous syndrome, isobaric counterdiffusion, and other risks.

In general, the lower the nitrogen fraction in breathing gas, the lower the level of inert gas narcosis experienced by the diver. Because there is no commercially available open-circuit heliox training available, the decision was made to complete a training course based on trimix, which is standardized. The training program was designed to utilize trimix, as per the certifying agency training standards, allowing the divers to reduce their equivalent narcotic depth (END) to 100 ffw (30 mfw ) (*i.e.*, the same level of narcosis they would experience as though they were breathing air at that depth).

In addition, since trimix was not available commercially at either the training location in Santa Rosa, NM or at Lake Mead, training included instruction in the production of both trimix and the nitrox mixtures used for decompression.

Training of the five divers took place over a sixteen-day period in 2003. Curriculum of the program was patterned after IANTD Technical Diver, Trimix Diver, and Trimix Gas Blending standards (Anon, 2003a). Additional components were added to prepare the divers for the type of work they would be doing at depth in Lake Mead. Each diver did a minimum of 12 training dives. They were also responsible for mixing all of the gases they each utilized during those dives. Some of the course objectives included training in use of double cylinders, use of stage cylinders, gas switching, decompression procedures, surface air consumption (SAC) rate determination, gas management planning, emergency procedures, and breathing gas selection.

Equipment used by each of the divers included the following: back-mounted double 120 $ft^3$ (19 L) cylinders with a dual valve non-isolation manifold, two 80 $ft^3$ (11 L) stage cylinders containing multiple decompression gases, 6.0 $ft^3$ (1.0 L) air drysuit inflation cylinder, regulators for all of the preceding, lift bag and reel, canister light, various slates and dive tables, Hydrospace Engineering Explorer (HSE) dive computer, multiple cutting devices, drysuit, watch, mask and fins.

Training decompression was planned using the IANTD tables (Mount, 1998), which are based on a Buhlmann algorithm. Tables were backed up by the HSE computers. The HSE computer has nine different models programmed into the units. Computational formulas (CF) 0-2 are based on the RGBM model developed by Wienke. CF3 to CF9 are based on the Buhlmann algorithm, and are progressively more conservative. Use of the RGBM model was rejected due to the SRC dive team's concerns with validation and total operational experience. CF3 was utilized for all of the dives. In addition, a deep stop (halfway between maximum depth and the first required decompression stop) of two minutes was added to the required decompression, with the maximum bottom time reduced by that time.

In all cases, computers allowed for a shorter decompression time and quicker ascent time than did the tables, as would be expected because the training dives were not true square profiles. However, had there been an emergency mandating a minimal ascent time, the computer parameters for required decompression would have been followed.

Progressively deeper training dives were made at Rock Lake, to a maximum depth of 190 ffw (58 mfw). Altitude corrections were applied to the tables due to the 7,000 foot (2,133 m) elevation of the highway between the dive site and nearest medical facilities in Albuquerque (dive site elevation was 5,000 ft (1,524 m). This yielded an equivalent physiological depth of 230 fsw (70 msw). Bottom times were as much as 27 minutes, resulting in average decompression times of 75 minutes.

Nitrox was generally used as the bottom gas for dives 100 ffw (30 mfw) and shallower. On deeper dives, various Trimix blends were used, ranging from Tx28/32 to Tx18/40, etc (Tx18/40 denotes a mixture containing 18% oxygen, 40% helium, and 42% nitrogen). Decompression was conducted using EAN32 (a nitrox mixture containing 32% oxygen) for decompression stops in the 110 ffw (33 mfw) to 31 ffw (10 mfw), and oxygen from 30 ffw (9 mfw) to the surface. (Note: this exceeds AAUS and NOAA recommendations.) This added an additional margin of safety relating to decompression sickness, as the tables called for the use of EAN35 and EAN75 respectively.

Breathing gas was blended on site using a continuous blend methodology. A mixing stick capable of accepting oxygen, helium, and air simultaneously was utilized in conjunction with a Rix oil-free compressor. All final gas mixtures were analyzed for oxygen and helium fractions during blending and each mix was analyzed using independent Oxycheq analyzers prior to each dive.

As the instructor, I preferred the safety and logistical advantages afforded by mixed gas CCRs, so during all training dives I used a PRISM Topaz rebreather. Tx10/50 was utilized as diluent for all of the deep dives (>100 ffw [30 mfw]). I carried sufficient bailout gas to get either myself or any one of the NPS divers to the surface in the event of an emergency.

During the class, the dive team conducted extensive research into comparisons of various decompression algorithms, Trimix fractions and heliox use. Upon course completion, three days of concentrated deep diving physiology and dive accident prevention and management were conducted by Dudley Crosson of Delta P, Inc., a company that provides diving consultation to commercial companies, military and NASA.

## Operational Diving Procedures

### *B-29 Plane Wreck*

The initial objective of LAME management was the archeological assessment of a B-29 that crashed into the lake during a scientific mission in 1948. At the time of the two field deployments in 2003 and 2005, the lake level was about 1,140 ft (347 m), yielding a maximum diving depth of 185 ffw (56 mfw).

During fieldwork SRC divers decided to use heliox instead of trimix as the bottom gas, based on their research. There were several reasons for this change. First, trimix decompression models are not as well validated as heliox models. Heliox has been in use by the US Navy (Anon, 1999), commercial diving corporations, and DCIEM (Anon, 1995) for decades, and there has been extensive scientific experimentation with this mixture. Heliox tables had varying amounts of controlled validation testing, were readily available, and had significant operational history. In contrast, the IANTD Trimix tables, released in 1993, had, in the opinion of the dive team, insufficiently rigorous scientific validation and limited operational usage.

Second, all of the divers felt varying degrees of narcosis and apprehension during the deeper training dives in Rock Lake. This was a cold, dark environment, very similar to that expected in Lake Mead. Based on the training experience, elimination of all nitrogen from the bottom mix would facilitate the research work and accident management and also provide the best risk minimization approach. To minimize field logistics and to ensure consistency of heliox mix, commercial blended heliox with an oxygen fraction of 0.20 ($HeO_220$) would be used for OC. Gas was boosted to final filling pressures using an electric Masterline oxygen-clean booster.

This change was not without downsides. The cost-per-dive-per-diver increased from about $25 to about $100. The increased helium fraction increased decompression time and also induced a potentially greater heat loss in the divers. In SRC's view, the risk minimization offered by heliox was worth the increased cost.

This project required development of a project-specific Safe Practice Manual that included a Project Dive Emergency Plan. Some key elements of the diving protocol may be relevant to others. Bottom mix was normoxic heliox ($HeO_220$) premix on OC or heliox diluent containing 5-15% oxygen with a set point of 1.3 atm when using a constant $PO_2$ heliox in rebreathers. The only approved dive tables for this project were the DCIEM tables and 'straight' Buhlmann tables, and the HSE Explorer or VR3 computer using the straight Buhlmann algorithm calculated for EAN32 decompression. However, during operations surface-supplied 100% $O_2$ from 30 ffw (9 mfw) to surface was required, and all stops shallower than 20 ffw (6 mfw) were conducted at 20 ffw (6 mfw). Rebreather divers adjusted $PO_2$ accordingly.

Fieldwork was conducted for 14 days in 2003, 10 days in 2005, and two deployments of 16 days and seven days in 2006. During that time diving operations were conducted in three-day segments, with the fourth day being an enforced break from diving. This was done to eliminate concerns with long half-time compartment loading and to provide an extended break for pulmonary oxygen toxicity exposure. Divers were limited to one deep dive per day.

Initial site assessment was done using side scan sonar and ROVs. ROVs were utilized nearly every day throughout the project to augment the data collected by the divers. They were also used to penetrate and record images and water quality in the plane's interior, which was inaccessible to the divers (access would have had significantly detrimental effects to the B-29).

All diving operations were conducted from a 40-ft (12-m) NPS maintenance barge, the *Tamarisk*. The barge was motored out daily and secured over the site in a four-point mooring. All dive equipment, emergency gear like AED and first aid kit, surface supplied oxygen, and other gear were kept on the barge. The barge was moved in from the site every night because of weather uncertainty (wind and squalls could blow up at virtually any time).

Conditions at depth were extremely dark. In the summer months in which the project was run in 2003, the upper 50 ft (15 m) of the water column was a very dense plankton assemblage. Below this layer, ambient light was extremely limited, being inadequate to read gauges, for example. For this reason, all divers carried 10-watt HID canister lights, as well as one to three backup lights per person. In addition, a custom built frame holding four 1,200-watt HMI lights was deployed at a depth of about 130 ffw (39 mfw). These lights were powered by three generators located on the surface. The light provided by these HMIs enabled the divers to work most of the time without using their individual lights, and greatly facilitated video and photographic documentation.

Water temperature at depth was about 52°F (11°C). Air temperatures ranged as high as 105°F (40°C). This was of concern because of dehydration issues, especially with the suited standby diver. Conscious efforts were taken to keep all of the divers adequately hydrated, including providing drinking water in Camelback bags at the decompression stages.

A triangular shaped decompression stage was constructed from PVC pipe for the project. Each side of the triangle was eight feet (2.5 m) long, sufficient for two divers to comfortably decompress on each side. The assembly consisted of two levels. The decompression stage was deployed prior to commencing operations every day, with the two stages at 30 ffw (9 mfw) and 20 ffw (6 mfw) respectively. The stage was suspended by a single line which splint about 10 ft (3 m) below the surface to each corner of the shallower decompression stage. One corner of the deeper stage was secured to the descent/ascent line used by the divers.

The descent line was moored to a 200 lb (90 kg) concrete block deployed for that purpose. It was located about six feet (2 m) from the starboard wing. Attached to block was an 80 ft$^3$ cylinder filled with heliox bottom mix. A cylinder containing EAN32 was tied to the line at 110 ffw (33 mfw), the location where the team members would switch from their heliox bottom mix to a nitrox decompression mix. These cylinders were left in their respective locations for the duration of the project and were for emergency use only. Another cylinder of heliox was staged on the bottom at the trailing edge of the port wing near the fuselage. All cylinders were wrapped with photoreflective tape and left with their valves closed. The first dive team of the day checked the submersible pressure gauges of each cylinder at the beginning of their dive to ensure that the cylinders were full.

Bottom times ranged from 20 to 45 minutes. Various decompression models were compared, including USN, DCIEM, and HSE Explorer. Because the USN and DCIEM tables utilized surface oxygen decompression (involving egress of the diver from the water and pressurization in a chamber for surface decompression, software derived HSE tables were followed for the dives. Again, a straight Buhlmann-based algorithm was used. Total decompression times ranged to approximately two hours.

Open-circuit divers utilized the same decompression gas mixtures previously listed. Again, oxygen decompression began at 30 ffw (9 mfw), yielding a $PO_2$ of 1.9 atm. While this exposure is greater than that recommended by the recreational sport diving agencies, AAUS or NOAA, SRC divers have been using this approach for decompression purposes since the inception of the original dive team in 1975 without incident. Members of SRC pioneered the use of pure oxygen for decompression without altering times for scientific diving (Murphy, 1978; Lenihan, 2002). SRC experience determined that the benefits of increased inert gas washout (maximum alveolar tissue pressure gradient) outweighed CNS oxygen toxicity issues. To alleviate concerns with CNS toxicity, oxygen was breathed for 20-minute intervals, followed by five minute air breaks. The air break times were not counted towards the required decompression obligations, again adding a margin of safety. The last decompression stop was at 20 ffw (6 mfw), followed upon completion by a two minute ascent to the surface.

Oxygen was supplied from the surface. Four 200 $ft^3$ (38 L) cylinders were manifolded together to supply the gas. Only three were online at any given time, with one kept in reserve to cover supply failures. Six second stages on individual hoses were attached at the deeper stage by the safety diver prior to commencing research diving operations. Two emergency supply cylinders of oxygen were placed at both decompression levels, as well as two air cylinders for air breaks. Each cylinder had its own regulator, with two second stages each. Water in Camelback bags was also placed at each level, allowing the divers to stay hydrated during the decompression stops.

A topside dive supervisor maintained logs of all entries and exits, as well as overseeing pre-dive safety equipment emplacement.

Again, for these dives I utilized a CCR, using $HeO_2 10$ in the diluent cylinder. In 2003, I used a PRISM Topaz. The factory supplied 19 $ft^3$ (3 L) cylinders were replaced with 42 $ft^3$ (7 L) cylinders, allowing additional available onboard bottom gas for open-circuit bailout. In 2005, a stock Evolution CCR was used, and in 2006 a stock Dive Rite Optima with 27 $ft^3$ (4.5 L) cylinders was used. Drysuit inflation gas was supplied by an off-board cylinder containing either air or nitrox.

### *Aggregate Plant*

During the early 2006 field season, various structures associated with the aggregate plant used to construct Hoover Dam were investigated and documented. The aggregate sorting and washing facility was a huge industrial complex designed to provide clean aggregate of differing sizes which, when mixed with cement, would form concrete with specific structural properties for use in different sections of Hoover Dam. In all, more than 118 million cubic feet of concrete were poured to create the dam. Following completion of the dam, most of the facility was removed, but significant portions remained and were subsequently submerged by rising lake levels.

Dives in 2006 were conducted from February to March and in December, eliminating the problems associated with summer heat and dehydration of the divers. Shallow visibility was also better due to reduction of plankton density in the winter months.

This phase of the project used mixed modes of diving. After the 2005 field season, SRC divers had decided to utilize CCRs for their diving. In addition to the units used and evaluated during prior field seasons, the SRC also considered the USN Mark 16, Ourobouros, Megalodon, Oceanic and Inspiration CCRs. The team selected the AP Evolution as the best currently available unit for their needs, and accordingly two divers spent two weeks training on the unit in December 2005. Further experience was gained during field work in Biscayne National Park after the completion of training, and while completing geological and hydrological studies in Montezuma Castle National Monument in January 2006.

Training for the use of helium-based diluents was accomplished at Lake Mead prior to beginning research activities. SRC divers had in excess of 50 hours each using the Evolutions prior to beginning this advanced training. Maximum depth of the training dives was 210 ffw (64 mfw).

Two additional divers from NOAA joined the SRC team during this phase of the project. In all, there were three CCR divers and three O/C divers.

While no particular effort was made to match divers using the same mode of diving, dive planning considerations generally led to this result. In those dives where mixed CCR and OC modes were utilized, the CCR divers always carried sufficient OC bailout gas to aid their buddies in the event of a gas supply failure emergency.

Prior to being paired with CCR divers, OC divers were provided a basic overview of CCR theory and operation. They were also instructed in CCR failure modes, and how to handle CCR emergencies and CCR specific rescue procedures. This basic level of education permitted them to monitor CCR partners, and would have allowed them to provide emergency assistance had it been required.

The shallowest site was the water clarifier, originally built to remove sediment from the water used to clean the aggregate prior to use in the dam concrete. The clarifier ranged from 3-55 ffw (1-17 mfw) in depth in early 2006. By December 2006, portions of the clarifier were above the surface due to reservoir lowering. The second site surveyed was a section of railroad tracks used to transport materials to and from the aggregate plant. These were 110-115 ffw (33-35 mfw) deep.

The bulk of the aggregate plant included railroad hoppers, piles of aggregate, and various equipment associated with the aggregate plant. This third site contained at least four areas in which divers entered structures in which direct access to the surface was not possible. During these penetrations (maximum linear distance of about 70 ft (21 m) at a maximum depth of 155 ffw (47 mfw) guidelines were used as navigational aids. Guidelines were also used when swimming from one structure to the next to ensure that divers would be able to return to the upline and the decompression trapeze at the end of the dive.

In general, the same decompression protocols established during the 2003 and 2005 B-29 portion of the project were utilized. However, because part of the team was in residing Boulder City instead of on a houseboat at lake level, an altitude adjustment of 3,000 ft (900 m) was incorporated into the decompression model used to generate the decompression tables. Because NOAA divers were using VR3 computers, tables were generated using both the VR3 and HSE models, with the more conservative figures used for any given dive.

*Catalina PBY-5A Wreck*

The most recent diving activities took place during December 2006. The lake level at this time was ~1,127 ft (344 m). The primary focus during this field deployment was documentation of a Catalina PBY-5A flying boat which crashed and burned during a water landing in 1949 (Anon, 1949), sinking soon after hitting the water. Maximum depth reached during this phase was 191 ffw (58 mfw).

The primary difference during this deployment was the fielding of a complete CCR dive team. Plans called for using three rebreather divers, two diving at any given time, and one situated on the surface as a standby diver. The goal was to minimize dive and support equipment, and simplify gas supply logistics.

Unfortunately, one of the divers was unable to dive, due to a pre-existing problem with alternobaric vertigo. To accommodate this issue, plans were modified to utilize an OC diver as the standby diver for all dives. Since he was not diving daily, his gas cylinders only needed to be filled one time at the beginning of the project. Therefore, total gas requirements for the project increased by a negligible amount.

Heliox10 was used as the diluent for these dives. Divers carried two 46 $ft^3$ (8 L) bailout cylinders, one containing $HeO_2$20 for use on the bottom, and a second of oxygen for decompression. For suit inflation divers carried 6 $ft^3$ (1 L) cylinders of air.

Again, general decompression procedures remained the same as previous field deployments. Both VR3 and HSE computers were used to back up the Vision electronics on the Evolutions during this phase, with Buhlmann-based HSE tables cut to determine decompression obligations. Divers were again residing in Boulder City, so the same altitude adjustment was used. The dives were done using a set point of 1.3 atm. Since decompression was done on the CCRs instead of OC gas, $PO_2$s were increased to 1.4 atm for the decompression, and no air breaks were utilized. To incorporate a further margin of safety, the tables cut for the dives were based on a set point of 1.1 atm for both the dive as well as the decompression. OC nitrox, surface supplied oxygen and OC air was available to the divers in the event of a CCR failure.

## Emergency Procedures

A variety of plans were defined in advance of actual dive operations to cope with any foreseeable emergencies that might occur. These were defined in the SRC Safe Practices Manual, which was revised prior to every new field deployment (Murphy and Seymour, 2003-2006).

Key components of this plan were communication and transport management. Central dispatch was notified immediately prior to initiation of diving activities, and again when divers had exited the water. The nearest operational chamber was identified and contacted prior to the initiation of all projects and transport protocols established in the event of need. During the time NOAA personnel were diving, a portable recompression chamber and operator were on site, and all personnel were briefed on its use prior to onset of diving operations.

A standby diver was suited and ready to deploy within five minutes whenever deep diving operations were underway. A dive supervisor was always present on the surface to oversee operations and maintain dive time and depth information.

General emergency plans included caching cylinders of bottom gas at two locations on the bottom, typically at the base of the down line and at a site near where the divers would be working on the structure. Emergency decompression gases were cached on the upline at or below the depth of planned use (EANx). At the decompression trapeze, a redundant cylinder of oxygen was clipped off with the valve turned off in the event of catastrophic failure of the surface supplied equipment, and extra air cylinders were staged for air break usage. In addition, one cylinder each of bottom gas mix, EAN34, oxygen, and air were available on the surface rigged and ready to deploy via the standby diver if needed.

All divers carried the decompression schedules on slates on every dive. They each also carried contingency tables for worst case scenarios, in case they exceeded planned maximum depth by 10 ffw (3.0 mfw) or time by 10 and 15 minutes.

Divers carried a separate slate with a list of predetermined emergency scenarios (equipment failure, out of bottom gas, out of EANx, out of oxygen, DCS, lost buddy, lost upline, etc). This allowed the diver to merely circle the appropriate problem in the event of difficulties and send it to the surface via lift bag. At the surface it could be retrieved, and the standby diver deployed knowing what to expect and carrying any necessary equipment or supplies. Each lift bag was clearly labeled with the diver's name so surface personnel would know who was experiencing difficulties.

Lines were run on the bottom to/from the down line, insuring navigational capability back to the line for ascent. Whenever structures were penetrated, guidelines back to the entrance were utilized. During the 2006 operation, divers also tagged the upline with a waterproof strobe light to facilitate reacquisition in the event of light failure or siltout.

Rebreathers were prepared and maintained after the dives by following detailed checklists. The checklists used were developed in greater detail than those provided by the various manufacturers. Any problems with CCRs were resolved prior to diving.

OC divers were trained on what responses were necessary should a CCR dive partner experience difficulties while underwater. In this manner they were prepared to provide effective assistance if necessary. CCR divers carried OC gas appropriate for whatever depth they were at for both self rescue as well as buddy assistance. Decompression schedules for OC bailout from depth with a worst case depth and time profile were carried as a backup to the closed-circuit decompression schedules should a bailout at depth become necessary.

Rebreather divers were required to use fresh carbon dioxide absorbent fills for any dive deeper than 150 ffw (46 mfw). Emergency procedures for recovery from different rebreather problems or failures were practiced or reviewed before each field deployment. Bailout procedures were similarly practiced.

## Discussion

During the three years that deep diving operations have been used to support research by the SRC, 118 helium-based deep dives have been conducted without incident (2003, 48 dives; 2005: 16 dives; 2006: 54 dives). Both open- and closed-circuit dive modes worked well and these projects offer the opportunity to compare the logistics, costs and efficiencies among OC, mixed and rebreather field operations.

The SRC protocols have evolved through time, with their Safe Practices Manual reflecting this evolution. In general, the more active divers have switched from an open-circuit to a closed-circuit mode. This has resulted in more cost-effective diving operations, as gas costs have been enormously reduced (by as much as 95% for consumables, including gas, batteries, and absorbent cost).

Rebreather use has also resulted in an overall increase in efficiency. The time needed to prepare the CCRs and maintain them after the dives, including filling cylinders, has been less than half that needed to fill the larger double cylinders necessary for OC operations. This has freed more time for research and support activities, and it has also reduced diver fatigue and stress.

The SRC divers made several modifications to their Evolutions to facilitate maintenance chores. Primary among these was changing the manner in which the counterlungs attach to the unit. The standard lungs were cut off the mounting harness, and Fastex clips utilized to attach them. With this system, the lungs and breathing hoses may be removed from the unit and easily carried inside to a comfortable location for disinfecting. They also had special quick-release mounting brackets designed so that accessories like video camera battery packs, small bailout cylinders and drysuit inflations systems can be quickly and easily attached and removed from the system.

Finally, rebreather use has reduced shipping and logistical costs and time expenditures. A fully supported CCR team can be deployed with the equipment, including gas supplies, in a large pick-up truck, while a similar open-circuit effort would require a fully laden panel truck. Conceivably, a fly-away capability could be reasonably easily established, so long as the appropriate gases are available at the research destination.

These benefits have some significant costs associated with them. The initial capital outlay of about $10,000 per diver, plus the associated training cost and time commitment (about four weeks for helium-based diluent use) is a serious barrier to entry for this mode of diving. Skill maintenance costs are also high, as CCR skills must be practiced to maintain currency. These issues reduced the available pool of fully qualified deep SRC divers from six persons to two during the time frame of this project.

Therefore, it would seem if deep diving operations are to be sporadic in nature or of limited scope, then an open-circuit approach is probably the most cost effective. If such operations are to be more extensive, and if the personnel turnover is low, then a closed-circuit approach may be justifiable.

With the use of CCRs, there has been a move away from using oxygen at 30 ffw (9 mfw) depths, reducing the planned oxygen exposure experienced by the divers from 1.9 atm to 1.4 atm. There has also been a shift in tools used to plan dive exposures from published tables to software developed tables, and from the HSE Explorer dive computer to the VR3 computer.

A variety of agencies have been involved in the SRC diving activities at Lake Mead. Some of these have fielded divers, other have participated as observers, surface research personnel, support personnel or collaborators. These have included, in part: other branches of the National Park Service, NOAA, Parks Canada, Lone Wolf Documentary Group, History Channel, the Outside Las Vegas Foundation, Forever Resorts, the National Park Service's Student Conservation Association, University of Nevada Las Vegas, Discovery Channel Canada, Our World Underwater Scholarship Program, PBS, Archaeology Magazine and Clark County Coroner's Office.

In some cases interagency differences in diving protocols have initiated modifications to the dive operation procedures. For example, NOAA's standards for mixed gas diving require an on site recompression chamber, and the use of different decompression planning tools than those used by SRC. In these cases, both agencies' standards were examined, and the most conservative of each was implemented for that portion of the project. Interagency involvement was seen as beneficial, as it raised new issues for consideration, fostered discussion of previously established policies, and generally resulted in a more robust diving operation. A beneficial discussion with the NOAA Dive Officer and SRC was initiated and is ongoing.

Diving efforts on this project have resulted in a wide variety of end products. These include, in part: active criminal investigative work leading to the recovery of objects illegally removed from some of the sites, survey work, maps, interpretative brochures and movie presentations, emplacement of mooring blocks and sub-surface navigational guidelines for use by the general public as sites are opened for visitation, water chemistry analysis, photographic and videographic libraries, resource assessments and baseline data collection and other site documentation (Chenoweth *et al*., 2004; Anon 2004, 2006).

Finally, these projects provide a model in which active research divers may utilize both open-circuit and closed-circuit modes of helium-based diving operations that may be exported to other agencies and projects.

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