A Selection from

Smithsonian at the Poles

Contributions to International Polar Year Science

Igor Krupnik, Michael A. Lang,
and Scott E. Miller
Editors

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Scientific Diving Under Ice: A 40-Year Bipolar Research Tool

Michael A. Lang and Rob Robbins

ABSTRACT. Approximately four decades ago, scientists were first able to enter the undersea polar environment to make biological observations for a nominal period of time. The conduct of underwater research in extreme environments requires special consideration of diving physiology, equipment design, diver training, and operational procedures, all of which enable this under-ice approach. Since those first ice dives in wetsuits and double-hose regulators without buoyancy compensators or submersible pressure gauges, novel ice diving techniques have expanded the working envelope based on scientific need to include the use of dive computers, oxygen-enriched air, rebreather units, bluewater diving, and drysuit systems. The 2007 International Polar Diving Workshop in Svalbard promulgated consensus polar diving recommendations through the combined international, interdisciplinary expertise of participating polar diving scientists, equipment manufacturers, physiologists and decompression experts, and diving safety officers. The National Science Foundation U.S. Antarctic Program scientific diving exposures, in support of underwater research, enjoy a remarkable safety record and high scientific productivity due to a significant allocation of logistical support and resources to ensure personnel safety.

INTRODUCTION

Milestones of U.S. Antarctic diving activities (Table 1) start with the first dive by Americans in Antarctic waters made just after New Year's Day in 1947 as part of Operation Highjump, the United States' first major postwar Antarctic venture. Lieutenant Commander Tommy Thompson and a Chief Dixon used "Jack Brown" masks and Desco® oxygen rebreathers. Early scuba divers braved McMurdo Sound's −1.8°C water with wetsuits and double-hose regulators. Equipment advances since then have led to the use of variable volume drysuits, buoyancy compensators (BCs), and dive computers. Because of their resistance to freezing, however, double-hose regulators were used almost exclusively in the McMurdo area from 1963 until 1990. Since then, single-hose regulators that also resist freeze-up failure have been used. From 1947 to 1967, research diving operations fell under the control of the U.S. Naval Support Force Antarctica and divers adhered to established U.S. Navy diving regulations. In 1967, James R. Stewart, Scripps Institution of Oceanography diving officer, established guidelines for the conduct of research diving in the polar

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TABLE 1. Milestones of USAP Dive Program (adapted from Brueggeman, 2003).

Date(s)	Milestone
1947	First dive by Americans in Antarctic waters, LCDR Thompson and Chief Dixon, as part of Operation Highjump, using Jack Brown masks and Desco oxygen rebreathers
1951	First Antarctic open-circuit scuba dive
1947–1967	Research diving operations under USN Support Force, Antarctica
1961–1962	Verne E. Peckham (Donald E. Wohlschlag project, Stanford University) logged 35 science dives tended topside on occasion by Arthur Devries and Gerry Kooyman
1962–1963	John S. Bunt (Donald E. Wohlschlag project, Stanford University) logged 7 science dives
1963–1964	G. Carleton Ray (New York Zoological Society), Elmer T. Feltz and David O. Lavallee logged 10 scuba dives
1963–1964	Gerald Kooyman started diving under ice with Weddell Seals with Paul K. Dayton tending topside
1963–1964	Willard I. Simmonds (Jacques S. Zaneveld project, Old Dominion University) logged 45 tethered science dives
1964–1965	Gerry Kooyman, Jack K. Fletcher and James M. Curtis logged 71 science dives
1965–1966	David M. Bresnahan (NSF OPP) and Leonard L. Nero dived on Zaneveld's project
1965–1966	G. Carleton Ray, Michael A. deCamp, and David O. Lavallee diving with Weddell seals
1967	NSF-SIO agreement for polar research diving (James R. Stewart)
1968	Paul K. Dayton benthic ecology project divers Charles Gault, Gerry Kooyman, Gordon Robilliard. Dayton has logged over 500 hundred dives under McMurdo ice
1978–1979	Dry Valley Lake diving: George F. Simmons, Bruce C. Parker and Dale T. Andersen
1987	USAP Guidelines for Conduct of Research Diving
1990	Double-hose regulators phased out in favor of single-hose regulators.
1992	AAUS Polar Diving Workshop (Lang, M.A and J.R. Stewart, eds.)
1995	RPSC on-site Scientific Diving Coordinator (Rob Robbins)
2001	NSF-Smithsonian Interagency Agreement for polar research diving (Michael A. Lang)
2003–2007	Svalbard ice diving courses (Michael A. Lang)
2007	International Polar Diving Workshop, Svalbard (M.A. Lang and M.D.J. Sayer, eds.)
2008	Smithsonian/NSF ice-diving regulator evaluation project, McMurdo (Michael A. Lang, P. I.)

regions for the National Science Foundation (NSF) Office of Polar Programs (OPP). Since 1995, Rob Robbins, Raytheon Polar Services Company, has served as onsite scientific diving coordinator. In 2001, Michael A. Lang, director of the Smithsonian Scientific Diving Program, enacted an Interagency Agreement between the Smithsonian Institution and the NSF for the management of the U.S. Antarctic Program (USAP) scientific diving program. As NSF OPP Diving Safety Officer (DSO), these responsibilities include, with the USAP Diving Control Board, promulgation of diving safety standards and procedures, evaluation and training of prospective divers, and authorization of dive plans. The USAP *Standards for the Conduct of Scientific Diving* (USAP, 1991) references the scientific diving standards published by the American Academy of Underwater Sciences (AAUS). Approximately half of the Principal Investigators (Table 2) are employees of AAUS organizational member institutions. The USAP researchers understand that polar diving demands the acceptance of responsibility for an increased level of risk and diver preparation. Polar conditions are more rigorous and demanding of scientific divers and their equipment than most other diving environments.

Approximately 36 scientists dive each year through USAP and have logged more than 11,400 scientific ice dives since 1989 (Figure 1). Average dive times are 45 minutes; generally, no more than two dives are made per day within the no-decompression limits. The USAP scientific diving authorization process requires submission of information on diver training and history, depth certification, diving first aid training (Lang et al., 2007) and drysuit experience. Minimum qualification criteria for NSF diving authorization include: (a) a one-year diving certification; (b) 50 logged open-water dives; (c) 15 logged drysuit dives; and, (d) 10 logged drysuit dives in the past six months. Somers (1988) described ice diver training curricula considerations. A pre-dive orientation and checkout dive(s) are done on site to ensure that the diver exhibits a satisfactory level of comfort under the ice with their equipment. Divers new to the Antarctic program are usually accompanying experienced Antarctic research teams and are thus mentored in an "apprentice" mode. However, divers must

TABLE 2. Principal Investigators and Co-PIs of USAP diving projects (1989–2006).

Investigator	Project
Amsler, C.	University of Alabama, Birmingham*
Baker, W.	Florida Institute of Technology/University of South Florida*
Barry, J.	Monterey Bay Aquarium Research Institute*
Bosch, I.	SUNY-Geneseo
Bowser, S.	NY Dept. of Health-Wadsworth Center
Conlan, K.	Canadian Museum of Natural History
Davis, R.	Texas A&M University*
Dayton, P.	Scripps Institution of Oceanography*
DeVries, A.	University of Illinois-Urbana
Doran, P.	University of Illinois-Chicago
Dunton, K.	University of Texas-Austin*
Harbison, R.	Woods Hole Oceanographic Institution*
Kaiser, H.	N/A
Kennicutt, M.	University of Texas-Austin*
Kim, S.	Moss Landing Marine Laboratories*
Kooyman, G.	Scripps Institution of Oceanography*
Kvitek, R.	California State University, Monterey Bay
Lang, M.	Smithsonian Institution*
Lenihan, H.	University of North Carolina*
Madin, L.	Woods Hole Oceanographic Institution*
Manahan, D.	University of Southern California*
Marsh, A.	University of Delaware
McClintock, J.	University of Alabama, Birmingham*
McFeters, G.	Montana State University
Miller, M.	Exploratorium, San Francisco
Moran, A.	Clemson University
Oliver, J.	Moss Landing Marine Laboratories*
Pearse, J.	University of California, Santa Cruz*
Ponganis, P.	Scripps Institution of Oceanography*
Quetin, L.	University of California, Santa Barbara*
Torres, J.	University of South Florida*
Wharton, R.	University of Nevada-Desert Research Institute
Wu, N.	Mo Yung Productions

*AAUS organizational member institution.

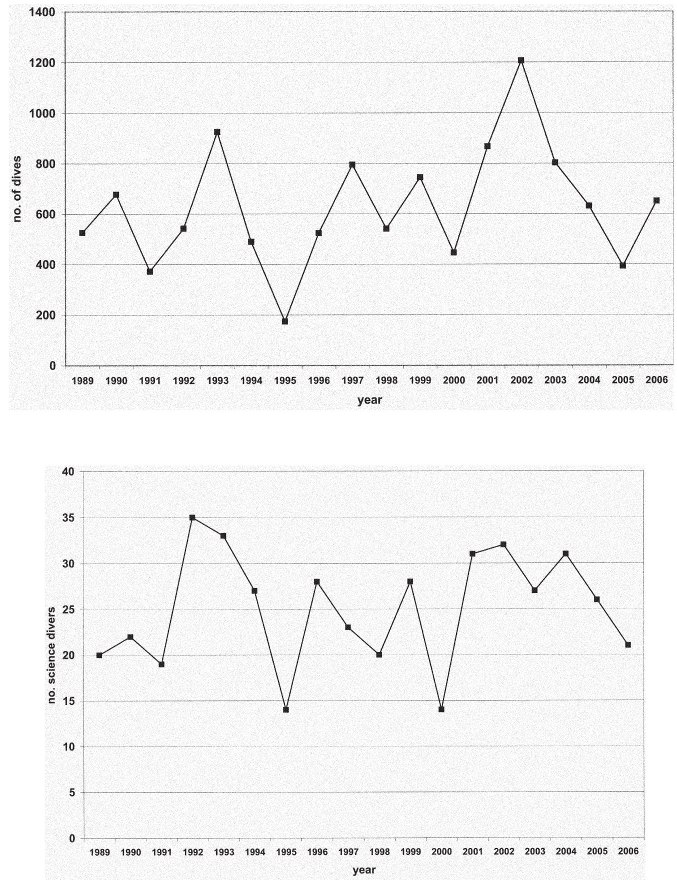

FIGURE 1. (top) USAP dive summary, 1989–2006. (bottom) USAP authorized diver summary, 1989–2006.

become proficient with the gear and techniques they will be using prior to deployment.

THE POLAR DIVING ENVIRONMENT

Ice Formation

Ice crystallization begins at the air-sea interface where the temperature differential is greatest. Because the air may be as much as 50°C colder than the water, heat conduction to the air from the water promotes the formation of ice. Under calm conditions, this *congelation* ice is composed of needles, small disks, and dendritic stars and will form a smooth sheet over the sea. When the freezing sea is subjected to wind and wave action, frazil ice crystals clump together into *pancake ice* (0.5 m to 2 m in diameter) that consists of roughly circular, porous slabs with upturned edges. If the water between them freezes, the "pancakes" may solidify and join together. Otherwise, pancake ice continually interacts with wind, waves, and other ice to create complex, many-layered floes of pack ice. When the ice sheet, whether congelation or frazil ice in origin, becomes a solid surface joined to the shoreline, it forms *fast ice*. Once the ice sheet is established, it continues to grow from beneath. Low-density seawater emanating from beneath ice shelves and floating glaciers undergoes adiabatic supercooling. *Platelet* ice crystals form in this supercooled water and float upward, accumulating in an initially loose and porous layer at the bottom of the surface ice sheet. This unfrozen platelet layer (1 cm to several m thick) continually solidifies by freezing, increasing the thickness of the ice sheet. The platelet layer forms a substrate for the growth of microbial communities dominated by microalgae fed upon by amphipods and ice fish. Ice may also crystallize on the benthos. This *anchor ice* generally forms at depths of 15 m or less, attaching to rocks and debris—and even to live invertebrates. If enough ice forms on these objects, they will float up and may become incorporated into the ice sheet.

Fast Ice

Diving conditions are usually associated with solid fast-ice cover for most of the austral diving season at McMurdo Station (annual average thickness 2 m, multiyear 4 m), limited freezing at Palmer Station (under 30 cm), periodically in the Svalbard fjords (average 1 m), and the perennially ice-covered Dry Valley lakes (greater than 6 m; Andersen, 2007). A solid fast-ice cover provides a calm, surge-free diving environment and offers a stable working platform with no surface wave action. Fast-ice strength and thickness varies with time of year and ambient temperature affecting diving operational support. The under-ice topography varies dramatically at dive site, time of year, microalgal activity, ocean current, age of ice, and other oceanographic and physical factors. When viewed from below, a fast-ice sheet may appear relatively homogenous as a hard, flat surface but in places can be punctuated by cracks and openings that appear as bright lines in an otherwise dark roof. If platelet ice is present, the underside of the ice appears rough and uneven. Areas of multiyear ice and thick snow cover are darker. Where pressure ridges and tidal cracks are present, the under-ice topography has more relief. Large and small chunks of broken ice may jut down into the water column in profusion, creating an environment reminiscent of cave diving. *Brine channels* or *ice stalactites* form as seawater cools and freezes and salt is excluded. This salt forms a supercooled brine solution that sinks because of its increased density and freezes the seawater around it resulting in a thin, hollow tube of ice stretching down from the underside of the ice sheet. These brine channels can reach several m in length and may appear singly or in clusters.

Pack Ice

Fast-ice diving differs from pack-ice diving (Quetin and Ross, 2009, this volume), where broken ice cover usually eliminates the need to cut access holes for diving because of easy access to the surface. The pack-ice environment tends to be more heterogeneous than that of fast ice. Ice may be present in all stages of development and the floes themselves may vary in size, age, structure, and integrity. Pack-ice divers will find themselves under an ever-shifting and dynamic surface and wave action and currents must be considered. At sites where the pack ice is forced against the shore and is solid but unstable, an access hole will have to be opened near shore in shallow water. Tidal fluctuations may alter the size of dive holes or vary the water depth under the holes.

Underwater Visibility

In August and September in the McMurdo region, underwater visibility may range up to a record 300 m. As solar radiation increases during the austral summer, an annual plankton bloom develops and quickly diminishes visibility to as little as 1 m by late December. Other water visibility factors influencing the polar regions include glacial melt and wind and temperature conditions. Visibility in the open waters of the Antarctic Peninsula may vary from 300 m to less than 3 m, depending on plankton densities and sea state. As glacial or sea ice melts, the resulting water may form a brackish water lens over the seawater. Visibility within these lenses is markedly reduced, even when the visibility in the water is still good otherwise. It may be possible to lose sight of the entry hole even when divers are near the surface.

POLAR DIVING OPERATIONS

Dive Access through Ice

Tidal action, currents, and other forces produce open cracks and leads that divers may use to enter the water. Divers working from USAP research vessels often use the leads cut by the vessel for their access to the water (Quetin and Ross, 2009, this volume). A hydraulically operated mobile drill can be used to cut 1.3 m diameter holes in ice that is over 5 m in thickness. In addition to the primary dive hole, at least one safety hole is required. Hole melters consisting of coiled copper tubing filled with hot circulating glycol or alcohol are used to open a clean, 1 m diameter hole in the thick ice cap that covers the freshwater Dry Valley Lakes (Andersen, 2007), taking from several hours to several days. Chain saws can also be used to cut an access hole through ice that is 15 to 60 cm thick. Access holes are cut into square or triangular shapes and made large enough to accommodate two divers in the water simultaneously. Another method is to use Jiffy drills that bore pilot holes in ice 15 to 30 cm thick and then saws can be used to cut a large dive hole between them;

attaching ice anchors to the chunks of ice allows for easy removal once they are sawed free. For ice from 15 to 25 cm thick, ice saws and breaker bars (2 m lengths of steel pipe or solid bar with a sharpened tip) are used to cut and break away the ice to form a hole. Divers enter the water through pack ice from shore, from an inflatable boat launched from shore or a research vessel, or from large ice floes or a fast-ice edge.

If dive holes are required in ice thicker than 5 m or in ice out of range of the mobile drill, explosives may be necessary. However, the use of explosives is generally discouraged for environmental reasons and requires several hours of clearing ice from the hole before a dive can be made.

Fast-ice diving requires one or more safety holes in addition to the primary dive hole. During times of the year when air temperatures are extremely cold, dive holes freeze over quickly. Positioning a heated hut or other portable shelter over a dive hole will delay the freezing process. Solar powered electric muffin fans are used to blow warm air from near the ceiling of the hut to the ice hole through a plastic tube. Down lines must mark all holes available for use on each dive because safety holes that are allowed to freeze at the surface are hard to distinguish from viable holes while diving under the ice.

Down Lines and Tethers

A down line is required on all untethered dives conducted from fast ice or any other stable overhead environment with limited surface access. Specific down line characteristics and components are described by Lang and Robbins (2007).

A minimum of one supervisor/tender per dive is required. Because they are a critical part of the diving operation and the first responders in case of accident, tenders receive training in diving first aid (Lang et al., 2007), radio use and communication procedures, scuba gear assembly, tether management, and vehicle or boat operation.

Dives conducted under fast ice where there is a current, reduced visibility or open blue water, or where the water is too shallow to maintain visual contact with the dive hole, require individual diver tethers that are securely attached at the surface. Use of the T- or L-shaped tether system is not ideal, making line-pull communication signals difficult and tether entanglement a possibility. Surface tender training is necessary to maintain enough positive tension on the tether line to immediately recognize line-pull signals from the safety diver, without impeding the activity or motion of the scientists working under the ice. The safety diver's function is to keep tethers untangled, watch for large predators and communicate via line-pull signals to the surface and other working divers.

Other hole-marking techniques to further protect against loss of the dive hole are snow removal (straight lines radiating outward from the dive hole that are very visible from under water) and benthic ropes which consist of 30 m lines laid out by divers when they first reach the benthos, radiating outward like the spokes of a wheel from a spot directly beneath the dive hole and marked so that the direction to the dive hole is clearly discernible.

Polar Diving Equipment

Members of the dive team take particular care in the selection and maintenance of polar diving equipment (Lang and Stewart, 1992; Lang and Sayer, 2007). Antarctic waters are among the coldest a research diver can expect to experience (−1.8°C in McMurdo Sound). In these temperatures, not all diving equipment can be expected to operate properly and freeze-ups may be more frequent. Diving under total ice cover also imposes safety considerations that are reflected in the choice of gear. We have developed specific care and maintenance procedures to ensure the reliability of life support equipment.

Divers are required to have two fully independent regulators attached to their air supply whenever they are diving under a ceiling. Modified Sherwood Maximus regulators (SRB3600 models, Figure 2) have been used successfully through the installation of a heat retention plate and adjustment of the intermediate pressure to 125

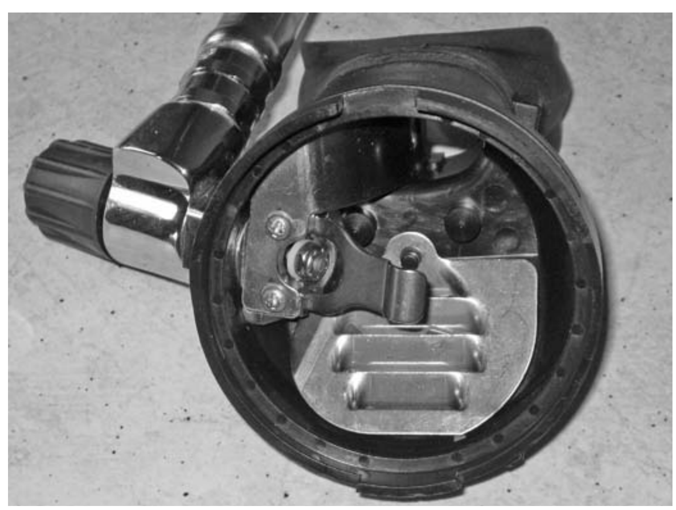

FIGURE 2. Sherwood Maximus SRB3600 second stage with heat retention plate.

psi. These units are rebuilt at the beginning of each season and with more than 7,000 dives have a freeze-up incident rate of 0.3 percent. Proper use and pre- and post-dive care substantially improves the reliability of ice diving regulators, which must be kept warm and dry before a dive. Divers should not breathe through the regulator before submersion except to briefly ensure that the regulator is functioning because of ice crystallization on the air delivery mechanism from breath moisture. This is particularly important if the dive is being conducted outside in very cold air temperatures. During a dive, a regulator is never used to fill a lift bag (small "pony bottles" are available for this purpose) because large volumes of air exhausted rapidly through a regulator will almost certainly result in a free-flow failure. Inflator hoses are attached to the backup regulator in case the air supply to the primary regulator must be turned off to stem a free flow. The backup regulator second stage is attached to the cylinder harness or buoyancy compensator (BC) such that it is readily accessible and easily detached. If the second stage is allowed to hang loosely from the cylinder and drag on the bottom, it will become contaminated with mud and sediment and may not function properly when required. After the dive, the regulators are rinsed and allowed to dry. During rinsing, care is taken to exclude water from the interior regulator mechanism. The diver ensures that the regulator cap is seated tightly, that the hoses and plugs on the first stage are secure, and that the purge on the second stage is not accidentally depressed during the rinse. The primary cause of regulator free-flow failure is from water entry within the mechanism that freezes once the regulator is used (Clarke and Rainone, 1995). Freshwater in the regulator may freeze simply with submersion of the regulator in seawater or upon exposure to extremely cold surface air temperatures. If multiple dives are planned, it is recommended to postpone a freshwater rinse of the regulator until all dives are completed for the day.

Inflator valves are also subject to free-flow failure, because of water entry into the inflation mechanism. Drysuit and BC inflators must be kept completely dry and hose connectors blown free of water and snow before attachment to the valve. When inflating a drysuit or a BC, frequent short bursts of air are used. Inflator buttons must never be depressed for longer than one second at a time because rapid air expansion, adiabatic cooling (5°C drop), and subsequent condensation and freezing may cause a free flow.

Buoyancy compensators need to allow unimpeded access to drysuit inflator and exhaust valves. Water must be removed from the BC bladder after diving and rinsing because freshwater in the bladder may freeze upon submersion of the BC in ambient seawater. In the McMurdo area, BC use is not currently required when the dive is conducted under a fast-ice ceiling because of the lack of need for surface flotation. A BC must never be used to compensate for excess hand-carried weight. Because of their buoyancy characteristics and durability in cold temperatures, steel, instead of aluminum, scuba cylinders are used.

Divers must wear sufficient weight, without overweighting, to allow for maintenance of neutral buoyancy with a certain amount of air in the drysuit. Runaway negative buoyancy is as great a safety problem to recover from as out-of-control ascent. Because of the amount of weight (30 to 40 lbs) and potential for accidental release, weight belts are not used. Diving Unlimited International (DUI) has developed weight and trim systems (Fig. 3) that retain the benefits of a harness while still allowing full or partial

FIGURE 3. DUI weight and trim system with bilaterally removable weight pockets (by pulling surgical tubing loops) and shoulder harness.

dumping of weight under water. The weight system prevents accidental release and improves comfort by shifting the weight load from the diver's hips to the shoulders.

Drysuit choice depends on the diver's preference, the requirement for range and ease of motion, and the options available with each suit. Vulcanized rubber suits must be used when diving in contaminated water because of post-dive suit decontamination requirements. Drysuits must be equipped with hands-free, automatic exhaust valves. Overinflation of the drysuit should never be used as a means to compensate for excess hand-carried weight. The choice of drysuit underwear is perhaps more important than the choice of drysuit construction material, because it is the underwear that provides most of the thermal protection. Many divers wear an underlayer of expedition-weight polypropylene with an outer layer of 400 g Thinsulate®. Dry gloves or mitts with an inner liner instead of wet gloves are now used with the drysuit. The DUI zipseal dry gloves enjoy widespread use and are effective at warm air equalization from the drysuit into the glove at depth. A disadvantage of these dry-glove systems is the complete lack of thermal protection if the gloves flood or are punctured, and the related inevitability of flooding the entire drysuit.

Severe cold can damage o-ring seals exposed to the environment requiring frequent cleaning and lubrication. Compressor care and adequate pre-operation warming are necessary to ensure a reliable supply of clean air checked by air-quality tests conducted at six-month intervals. Air filters and crankcase oil are scheduled to be changed on a regular basis. The filtering capacity of portable compressors is usually limited, necessitating air intake hose positioning upwind and well away from compressor engine exhaust. Manual condensate drains are purged frequently to prevent moisture contamination and freezing of the filter.

Each diver conducts a functional check of all equipment before each dive. Particular attention is paid to regulators and inflator valves. If leakage or free flow is detected at the surface, the dive is postponed and the gear serviced because it will certainly free flow at depth. All divers must be able to disconnect, with gloved hands, the low-pressure hose from a free-flowing drysuit inflator valve to avoid an uncontrolled ascent.

Because a drysuit must be inflated to prevent "suit squeeze" with increasing pressure, it is most efficient to regulate buoyancy at depth by the amount of air in the drysuit. Drysuits must be equipped with a hands-free exhaust valve (Lang and Egstrom, 1990). The BCs are considered emergency equipment, to be used only in the event of a drysuit failure. This procedure eliminates the need to vent two air sources during ascent, reduces the chance of BC inflator free-flow, and simplifies the maintenance of neutral buoyancy during the dive. The main purpose of air in a drysuit is to provide thermal insulation as a low-conductivity gas. Buoyancy compensators and drysuits must never be used as lift bags. When heavy items must be moved underwater, separate lift bags designed specifically for that purpose are used. Lang and Stewart (1992) concluded that there may be occasions when the drysuit diver is more at risk with a BC than without one. Accordingly, BCs are not required for dives under fast ice where a down line is deployed and the dive is not a blue-water dive.

Surface-Supplied Diving Under Ice

Robbins (2006) described USAP's surface-supplied diving activities, history, equipment, training, operations, and costs. By taking advantage of the equipment and expertise brought to the USAP 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 this mode long associated with industry but rarely used in the scientific arena. 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.

The USAP's experience with EXO-26 masks has been 11 free-flows in 106 dives (10.4 percent failure rate). AGA masks have had 2 free-flows in 26 dives (7.7 percent failure rate). These data come from dives in the Dry Valley Lakes where water temperatures range between 0°C and 2°C. The failure rate would be even higher in −1.8°C water of McMurdo Sound.

A minimum of two familiarization dives are made by each new surface-supplied diver over two days in addition to topside and underwater training. A three-person crew is the minimum personnel requirement including a supervisor/tender, a diver, and a suited standby diver using either scuba or surface supply.

Currently, the majority of surface-supplied diving is done utilizing 2-m tall high-pressure gas cylinders as an air source. A large 35 cfm/150 psi diesel compressor and smaller 14 cfm/125 psi gas compressor are available but used rarely for scientific diving operations. The USAP uses Kirby-Morgan Heliox-18 bandmasks and Superlite-17 helmets. While these units have a greater propensity to freeze and free-flow than Sherwood Maximus scuba regulators, their track record is as good as either the EXO-26 or AGA Divator full-face masks.

POLAR DIVING HAZARDS AND EMERGENCIES

Fast-Ice Diving Hazards

Lighting is often dim under a solid ice cover, particularly early in the austral spring when the sun is low on the horizon. The amount of snow cover and ice thickness will also attenuate light transmission. Microalgal blooms and increasing zooplankton during the austral summer reduces available light, making it difficult for divers to locate buddies, down lines, and underwater landmarks. High visibility early in the austral summer season may make under-ice or benthic objects seem closer than they are. This illusion may entice divers to travel farther from the access hole than is prudent.

The greatest hazard associated with fast-ice diving is the potential loss of the dive hole or lead. Access holes, leads, and cracks in the ice are often highly visible from below because of downwelling daylight streaming through them. However, dive holes may be difficult to see due to conditions of darkness or of covering the holes with portable shelters. Therefore, a well-marked down line is required for fast-ice dives. Divers maintain positive visual contact with the down line during the dive and avoid becoming so distracted by their work that they fail to take frequent note of their position in relation to the access hole or lead. Problems requiring an emergency ascent are serious, since a vertical ascent is impossible except when a diver is directly under the dive hole or lead. Additional safety holes ameliorate the danger of losing the primary dive hole but former dive holes that have frozen over may still look like safety holes from below. To eliminate confusion in a frequently drilled area, all active holes are marked with a down line.

Pack-Ice Diving Hazards

Pack ice is inherently unstable and its conditions can change rapidly, primarily from surface wind conditions. An offshore wind may blow pack ice away from the shoreline and loosen the pack, whereas an onshore wind may move significant quantities of pack ice against shorelines or fast-ice edges, obstructing what may have been clear access areas when divers entered the water. Similarly, increased wind pressure on pack ice may make driving and maneuvering an inflatable Zodiac more difficult or impossible. Under a jumble of pack ice, the topography is reminiscent of cave diving. The condition of the pack must be continually monitored by divers and tenders for changes that may affect dive safety and the entry area must be kept clear. Down lines and tethers can be disturbed by shifting pack ice, forcing dive tenders to be alert in keeping these lines free of moving ice.

Surface swells, even if only light to moderate, may cause pack ice to oscillate up and down. In shallow water, it is possible for a diver to be crushed between rising and falling pack ice and the benthos. At Palmer Station, surges from the calving glacier in Arthur Harbor may create a similar hazard. Divers avoid diving under pack ice if the clearance between the ice and the benthos is 3 m or less. In addition, lighting may be dim under a heavy pack-ice cover.

Open water develops in McMurdo Sound when the fast ice breaks up in late December or early January. In the Palmer region, any existing fast ice usually breaks up by the end of October. Pack ice may be present for another month or two, and intermittently after that, but open water generally characterizes the diving environment after early December. Kongsfjorden in Svalbard has not formed a substantial ice cover since 2005. Climatic conditions will cause variation in annual ice conditions.

Divers operating in open water and from small boats fly a "diver down" or "Alpha" flag to warn other boat traffic in the area. When diving from small boats a rapid exit from the water into the boat may be necessary. Because this can be difficult when fully laden with gear, lines with clips hang over the side of the boat to temporarily secure gear and a ladder facilitates diver exit.

When diving in blue water (a deep open water environment devoid of visual cues as to the diver's vertical position in the water column) blue water diving guidelines generally apply (Haddock and Heine, 2005). Divers are tethered and wear buoyancy compensators and a down line is deployed if conditions warrant. Divers operating under pack ice in blue water often perceive current increases. Wind action causes the pack to move, which in turn moves the water directly below it. This effect decreases with depth, such that divers in still water at 10 m will have the illusion of movement as the pack ice above them drifts.

Ice-edge diving is usually conducted in blue water, and it tends to be shallow (less than 10 m). The underside of the ice sheet provides a depth reference lacking in ice-free blue water dives. Divers watch continuously for leopard seals known to lunge out of the water to attack people at the ice edge. They may also lurk under the ice waiting for a penguin, or a diver, to enter the water. If penguins in the area demonstrate a reluctance to enter the water, it may be an indication that a leopard seal is nearby.

Marine Life Hazards

Few polar animal species are considered dangerous to the diver. Southern elephant seals (*Mirounga leonina*) and Antarctic fur seals (*Arctocephalus gazelli*) may become aggressive during the late spring/early summer breeding season. Crabeater seals (*Lobodon carcinophagus*) have demonstrated curiosity toward divers and aggression to humans on the surface. Leopard seals (*Hydrurga leptonyx*) have been known to attack humans on the surface and have threatened divers in the water. A case report of the single known in-water fatality caused by a leopard seal is described by Muir et al. (2006). Should any aggressive seal approach divers in the water, similar techniques to those protecting against sharks are applied. Polar bears (*Ursus maritimus*) and walrus (*Odobenus rosmarus*) in the Arctic are considered predatory mammals against which diving personnel must be safeguarded. Encounters with all of the aforementioned mammals are usually restricted to areas of open water, ice edges, or pack ice.

Divers in the fast ice around McMurdo may encounter Weddell seals (*Leptonychotes weddelli*) in the water. Occasionally a Weddell seal returning from a dive may surface to breathe in a dive hole to replenish its oxygen stores after a hypoxic diving exposure (Kooyman, 2009, this volume). Usually the seal will vacate the hole once it has taken a few breaths particularly if divers are approaching from below and preparing to surface. Divers must approach such a seal with caution, since an oxygen-hungry seal may aggressively protect its air supply. Weddell seals protecting their surface access will often invert into a head-down, tail-up posture to watch for rivals. Divers entering or exiting the water are particularly vulnerable to aggressive male Weddells, who tend to bite each other in the flipper and genital regions. There are no recorded incidents of killer whale (*Orcinus orca*) attacks on divers.

Polar Diving Emergencies

The best method to mitigate scuba diving emergencies is through prevention. Divers must halt operations any time they become unduly stressed because of cold, fatigue, nervousness, or any other physiological reason. Similarly, diving is terminated if equipment difficulties occur, such as free-flowing regulators, tether-system entanglements, leaking drysuits, or buoyancy problems. Emergency situations and accidents stem rarely from a single major cause and they generally result from the accumulation of several minor problems. Maintaining the ability to not panic and to think clearly is the best preparation for the unexpected. Most diving emergencies can be mitigated by assistance from the dive buddy, reinforcing the importance of maintaining contact between two comparably equipped scientific divers while in the water.

Loss of contact with the dive hole may require divers to retrace their path. Scanning the water column for the down line is done slowly and deliberately because the strobe light flash rate is reduced in the cold water. If the hole cannot be found, an alternate access to the surface may have to be located. Often there will be open cracks at the point where fast ice touches a shoreline. Lost divers will have to constantly balance a desirable lower air consumption rate in shallow water with the need for the wider field of vision available from deeper water. Maintaining a safe proximity to the surface access point has made losing the dive hole an extremely unlikely occurrence.

Loss of the tether on a fast-ice dive that requires its use is one of the most serious polar diving emergencies. Lost diver search procedures are initiated immediately (i.e., assumption of a vertical position under the ice where the tethered buddy will swim a circular search pattern just under the ceiling to catch the untethered diver). The danger associated with the loss of a tether in low visibility is mitigated if the divers have previously deployed a series of benthic lines. If a diver becomes disconnected from the tether down current under fast ice, it may be necessary to crawl along the bottom to the down line. To clearly mark the access hole divers deploy a well-marked down line, establish recognizable "landmarks" (such as specific ice formations) under the hole at the outset of the dive, leave a strobe light, a flag, or other highly visible object on the substrate just below the hole or shovel surface snow off the ice in a radiating spoke pattern that points the way to the dive hole.

The under-ice platelet layer can be several meters thick and can become a safety concern if positively buoyant divers become trapped within this layer, become disoriented, and experience difficulty extricating themselves. The most obvious solution is to exhaust air from the drysuit to achieve negative buoyancy. If this is not possible and the platelet layer is not too thick, the diver may stand upside down on the hard under surface of the ice so that the head is out of the platelet ice to orient to the position of the dive hole and buddy. Another concern is that abundant platelet ice dislodged by divers will float up and plug a dive hole.

Fire is one of the greatest hazards to any scientific operation in polar environments. The low humidity ultimately renders any wooden structure susceptible to combustion and once a fire has started, it spreads quickly. Dive teams must always exercise the utmost care when using heat or open flame in a dive hut. If divers recognize during the dive that the dive hut is burning they must terminate the dive and ascend to a safety hole or to the under surface of the ice next to the hole (but not below it) in order to conserve air.

Environmental Protection

There are research diving sites in Antarctica (e.g., Palmer sewage outfall, McMurdo sewage outfall, and Winter Quarters Bay) that must be treated as contaminated water environments because of the high levels of *E. coli* bacteria (that have been measured up to 100,000/100 ml) or the presence of a hydrogen-sulfide layer (e.g., Lake Vanda). Diving with standard scuba or bandmask, where a diver may be exposed to the water, is prohibited in these areas. Surface-supplied/contaminated-water diving equipment is used at these sites ranging from Heliox-18 bandmasks for use with a vulcanized rubber drysuit to Superlite-17 helmets that mate to special Viking suits.

All researchers must avoid degrading the integrity of the environment in which they work. In particular, polar divers should avoid over-collecting, to not deplete an organism's abundance and alter the ecology of a research site; unduly disturbing the benthos; mixing of water layers such as haloclines; using explosives for opening dive holes; and, spilling oil, gasoline, or other chemicals used with machinery or in research. Increased attention to Antarctic Treaty protocols on environmental protection and implementation of the Antarctic Conservation Act have made human–seal interactions a more sensitive issue. Dive groups should avoid Weddell seal breeding areas during the breeding season and their breathing holes in particular.

PHYSIOLOGICAL CONSIDERATIONS

Cold

Cold ambient temperature is the overriding limiting factor on dive operations, especially for the thermal protection and dexterity of hands. Dives are terminated before a diver's hands become too cold to effectively operate the dive gear or grasp a down line. This loss of dexterity can occur quickly (5–10 min if hands are inadequately protected). Grasping a camera, net, or other experimental apparatus will increase the rate at which a hand becomes cold. Switching the object from hand to hand or attaching it to the down line may allow hands to rewarm. Dry glove systems have greatly improved thermal protection of the hands.

The cold environment can also cause chilling of the diver, resulting in a reduced cognitive ability with progressive cooling. Monitoring the progression of the following symptoms to avoid life-threatening hypothermia is important: cold hands or feet, shivering, increased air consumption, fatigue, confusion, inability to think clearly or perform simple tasks, loss of memory, reduced strength, cessation of shivering while still cold, and finally hypothermia.

Heat loss occurs through inadequate insulation, exposed areas (such as the head under an inadequate hood arrangement), and from breathing cold air. Scuba cylinder air is initially at ambient temperature and chills from expansion as it passes through the regulator. Air consumption increases as the diver cools, resulting in additional cooling with increased ventilation. Significant chilling also occurs during safety stops while the diver is not moving. Polar diving requires greater insulation, which results in decreasing general mobility and increasing the potential for buoyancy problems. This also means that an increased drag and swimming effort, along with the donning and doffing of equipment, all increase fatigue.

Surface Cold Exposure

Dive teams are aware that the weather can change quickly in polar environments. While they are in the field, all divers and tenders have in their possession sufficient cold-weather clothing for protection in any circumstance. Possible circumstances include loss of vehicle power or loss of fish hut caused by fire. Boat motor failure may strand dive teams away from the base station. Supervisors/tenders on dives conducted outside must also be prepared for the cooling effects of inactivity while waiting for the divers to surface. In addition, some food and water is a part of every dive team's basic equipment. Besides serving as emergency rations, water is important for diver rehydration after the dive.

Hydration

Besides the dehydrating effect of breathing filtered, dry, compressed air on a dive, Antarctica and the Arctic are extremely low-humidity environments where dehydration can be rapid and insidious. Continuous effort is advised to stay hydrated and maintain proper fluid balance.

Urine should be copious and clear and diuretics (coffee, tea, and alcohol) should be avoided before a dive.

DECOMPRESSION

Mueller (2007) reviewed the effect of cold on decompression stress. The relative contributions of tissue N_2 solubility and tissue perfusion to the etiology of decompression sickness (DCS) are not resolved completely. Over-warming of divers, especially active warming of cold divers following a dive, may induce DCS. Divers in polar environments should, therefore, avoid getting cold during decompression and/or after the dive and if they feel hypothermic, wait before taking hot showers until they have rewarmed themselves, for example, by walking. The effect of cold on bubble grades (as measured by Doppler scores) may be the same for a diver who is only slightly cold as for one who is severely hypothermic. Long-term health effects for divers with a high proportion of coldwater dives should be considered in the future.

Dive computers were examined for use by scientific divers (Lang and Hamilton, 1989) and have now been effectively used in scientific diving programs for almost two decades in lieu of U.S. Navy or other dive tables. Currently, the decompression status of all USAP divers is monitored through the use of dive computers (UWATEC Aladin Pro) and data loggers (Sensus Pro). Battery changes may be needed more frequently because of higher discharge rates in extreme cold. Advantages of dive computers over tables include their display of ascent rates, no-decompression time remaining at depth, and their dive profile downloading function. Generally, no more than two repetitive dives are conducted to depths less than 130fsw (40msw) and reverse dive profiles for no-decompression dives less than 40msw (130fsw) and depth differentials less than 12 msw (40fsw) are authorized (Lang and Lehner, 2000). Oxygen-enriched air (nitrox) capability (Lang, 2006) and rebreather use have, to date, not been requested nor implemented by the USAP Diving Program. Cold and the physical exertion required to deal with heavy gear in polar diving can increase the risk of DCS. Furthermore, because of the polar atmospheric effect, the mean annual pressure altitude at McMurdo Station is 200 meters. Under certain conditions, pressure altitude may be as low as 335 meters at sea level. Surfacing from a long, deep dive (on dive computer sea level settings) to an equivalent altitude of 335 meters may increase the probability of DCS. Safety stops of three to five minutes between 10- to 30-foot (3.3 to 10 m) depths are required for all dives (Lang and Egstrom, 1990).

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